इंटरनेट मानक

Disclosure to Promote the Right To Information

Whereas the Parliament of India has set out to provide a practical regime of right to information for citizens to secure access to information under the control of public authorities, in order to promote transparency and accountability in the working of every public authority, and whereas the attached publication of the Bureau of Indian Standards is of particular interest to the public, particularly disadvantaged communities and those engaged in the pursuit of education and knowledge, the attached public safety standard is made available to promote the timely dissemination of this information in an accurate manner to the public.

“जानने का अधिकार, जीने का अधिकार”
Mazdoor Kisan Shakti Sangathan
“The Right to Information, The Right to Live”

“पुराने को छोड नये के तरफ”
Jawaharlal Nehru
“Step Out From the Old to the New”

IS 3716 (1978): Application Guide for Insulation Co-Ordination [ETD 19: High Voltage Engineering]

“ज्ञान से एक नये भारत का निर्माण”
Satyanarayan Gangaram Pitroda
“Invent a New India Using Knowledge”

Act Number 22 of 2005
The Indian Parliament
RIGHT TO INFORMATION

Made Available By
Public.Resource.Org

“ज्ञान एक ऐसा खजाना है जो कभी चुराया नहीं जा सकता है”
Bhartṛhari—Nītiśatakam
“Knowledge is such a treasure which cannot be stolen”

BLANK PAGE

BRUTUM FULMEN
IGNORANTIA JURIS NON EXCUSAT
PROTECTED BY COPYRIGHT

(Reaffirmed 2006)

Indian Standard

APPLICATION GUIDE FOR INSULATION CO-ORDINATION

(*First Revision*)

Second Reprint AUGUST 1989

(Incorporating Amendment No. 1)

UDC 621.316.91.048 (036)

© *Copyright* 1983

BUREAU OF INDIAN STANDARDS
MANAK BHAVAN, 9 BAHADUR SHAH ZAFAR MARG
NEW DELHI 110002

Gr 13 *December* 1978

Indian Standard

APPLICATION GUIDE FOR INSULATION CO-ORDINATION

(First Revision)

High Voltage Techniques Sectional Committee, ETDC 19

Chairman	*Representing*
SHRI V. R. NARASIMHAN	Central Electricity Authority, New Delhi
Members	
DEPUTY DIRECTOR (*Alternate* to Shri V. R. Narasimhan)	
SHRI K. S. BHARDWAJ	Punjab State Electricity Board, Patiala
SHRI A. K. CHOPRA (*Alternate*)	
DR S. C. BHATIA	Siemens India Ltd, Bombay
DR D. P. SAHGAL (*Alternate*)	
DR K. DAS GUPTA	The Calcutta Electric Supply Corporation Ltd, Calcutta
SHRI A. K. BARMAN (*Alternate*)	
SHRI V. B. DESAI	Jyoti Ltd, Vadodara
DR P. SATYANARAYANA (*Alternate*)	
SHRI V. S. MANI	Hindustan Brown Boveri Ltd, Bombay
SHRI K. S. MADHAVAN (*Alternate*)	
SHRI S. K. MUKHERJEE	National Test House, Calcutta
SHRI D. V. NARKE	Bharat Heavy Electricals Ltd, New Delhi
SHRI B. N. GHOSH (*Alternate*)	
SHRI P. N. SHRIVASTAVA (*Alternate*)	
SHRI V. H. NAVKAL	The Bombay Electric Supply & Transport Undertaking, Bombay
SHRI M. L. DONGRE (*Alternate*)	
PROF G. R. GOVINDA RAJU	Indian Institute of Science, Bangalore
DR B. I. GURURAJ (*Alternate*)	
SHRI K. S. SIVAPRAKASAM	Karnataka Electricity Board, Bangalore
SHRI H. M. S. LINGAIH (*Alternate*)	
SHRI V. SRINIVASAN	W. S. Insulators of India Ltd, Madras
SHRI K. THIRUVENKADATHAN (*Alternate*)	
SHRI T. V. SUBRAMANIAN	Tamil Nadu Electricity Board, Madras
SHRI S. KRIPANIDHI (*Alternate*)	

(*Continued on page* 2)

© *Copyright* 1983

BUREAU OF INDIAN STANDARDS

This publication is protected under the *Indian Copyright Act* (XIV of 1957) and reproduction in whole or in part by any means except with written permission of the publisher shall be deemed to be an infringement of copyright under the said Act.

(*Continued from page* 1)

Members	*Representing*
Shri Surendra Singh	U.P. Government Pottery Development Centre, Khurja
Shri Komal Singh (*Alternate*)	
Shri C. R. Varier	Crompton Greaves Ltd, Bombay
Dr G. Parthasarathy (*Alternate*)	
Shri P. J. Wadia	The Tata Hydro-Electric Power Supply Co Ltd, Bombay
Dr R. Ranjan (*Alternate*)	
Shri S. P. Sachdev, Director (Elec tech)	Director General, ISI (*Ex-officio Member*)

Secretary

Shri M. N. Murthy
Assistant Director (Elec tech)

CONTENTS

PAGE

0. FOREWORD 6
1. SCOPE 7
2. TERMINOLOGY 8
3. VOLTAGE STRESSES IN SERVICE 8
4. INSULATION WITHSTAND 17
5. PROTECTIVE DEVICES 25
6. CO-ORDINATION BETWEEN STRESSES AND WITHSTAND CONSIDERATIONS COMMON TO RANGES A, B AND C 31
7. CO-ORDINATION BETWEEN STRESSES AND WITHSTAND VOLTAGE FOR RANGE A 33
8. CO-ORDINATION BETWEEN STRESSES AND WITHSTAND VOLTAGE FOR RANGE B 43
9. CO-ORDINATION BETWEEN STRESSES AND WITHSTAND VOLTAGE FOR RANGE C 43

APPENDICES

APPENDIX A SURGE TRANSFERENCE THROUGH TRANSFORMERS ... 61

APPENDIX B VALIDITY OF SWITCHING AND LIGHTNING IMPULSE WITHSTAND TESTS, 50 PERCENT DISRUPTIVE DISCHARGE TEST AND 15 IMPULSES WITHSTAND TEST 72

APPENDIX C STATISTICAL EVALUATION OF THE PROTECTIVE EFFECT OF SPARK GAPS 80

APPENDIX D EXAMPLES OF APPLICATION 83

APPENDIX E CLEARANCES IN AIR BETWEEN LIVE CONDUCTIVE PARTS AND EARTHED STRUCTURES TO SECURE A SPECIFIED IMPULSE WITHSTAND VOLTAGE FOR DRY CONDITIONS 87

TABLES

TABLE 1 PROVISIONAL SCALE OF NATURAL POLLUTION LEVELS ... 32

TABLE 2 PROVISIONAL RELATION BETWEEN POLLUTION LEVELS, TEST LEVELS AND CREEPAGE DISTANCE 33

PAGE

TABLE 3 CHOICE OF THE INSULATION LEVEL OF CASE I EQUIPMENT (FOR EXAMPLE TRANSFORMER PROTECTED BY SURGE DIVERTERS) 84

TABLE 4 CHOICE OF THE INSULATION LEVEL OF CASE II EQUIPMENT (FOR EXAMPLE UNPROTECTED DISCONNECTING SWITCH)... 85

TABLE 5 RISK OF FAILURE OF INSULATION AS A FUNCTION OF THE RATED SWITCHING IMPULSE WITHSTAND VOLTAGES OF THE EQUIPMENT OF TABLE 4 86

TABLE 6A CORRELATIONS BETWEEN INSULATION LEVELS AND MINIMUM PHASE-TO-EARTH AIR CLEARANCES ... 88

TABLE 6B CORRELATIONS BETWEEN INSULATION LEVELS AND MINIMUM PHASE-TO-EARTH AIR CLEARANCES ... 88

FIGURES

FIG. 1 OVERVOLTAGES 18

FIG. 2 PROBABILITY OF DISRUPTIVE DISCHARGE OF INSULATION UNDER IMPULSE VOLTAGE 22

FIG. 3 MAXIMUM PERMISSIBLE CABLE LENGTH WITH SURGE ARRESTER OF LINE/CABLE JUNCTION ONLY 42

FIG. 4 EVALUATION OF THE RISK OF FAILURE OF A PIECE OF INSULATION 46

FIG. 5 SIMPLIFIED STATISTICAL METHOD 49

FIG. 6 CORRELATIONS BETWEEN RISK OF FAILURE (*R*) AND STATISTICAL SAFETY FACTOR (γ) FOR VARIOUS SWITCHING SURGE DISTRIBUTIONS 51

FIG. 7 CORRELATIONS BETWEEN RISK OF FAILURE (*R*) AND STATISTICAL SAFETY FACTOR (γ) FOR VARIOUS SWITCHING SURGE DISTRIBUTIONS 52

FIG. 8 CORRELATIONS BETWEEN RISK OF FAILURE (*R*) AND STATISTICAL SAFETY FACTOR (γ) FOR VARIOUS SWITCHING SURGE DISTRIBUTIONS 53

PAGE

FIG. 9 CORRELATIONS BETWEEN RISK OF FAILURE (R) AND STATISTICAL SAFETY FACTOR (γ) FOR VARIOUS LIGHTNING SURGE DISTRIBUTIONS 55

FIG. 10 CORRELATIONS BETWEEN RISK OF FAILURE (R) AND STATISTICAL SAFETY FACTOR (γ) FOR VARIOUS LIGHTNING SURGE DISTRIBUTIONS 56

FIG. 11 CORRELATIONS BETWEEN RISK OF FAILURE (R) AND STATISTICAL SAFETY FACTOR (γ) FOR VARIOUS LIGHTNING SURGE DISTRIBUTIONS 57

FIG. 12 BLOCK-DIAGRAM OF INSULATION CO-ORDINATION AND DESIGN 59

FIG. 13 INITIAL CAPACITIVE VOLTAGE SPIKE 62

FIG. 14 VALUES OF FACTOR 'r' 65

FIG. 15 DEFINITION OF THE INSULATION STRENGTH OF A PIECE OF EQUIPMENT AT THE TIME t AS A FUNCTION OF THE PARAMETER K 73

FIG. 16 FREQUENCY DENSITY OF THE MEASURED 90 PERCENT WITHSTAND STRENGTH OF A POPULATION OF APPARATUS... 75

FIG. 17 PROBABILITY OF AN EQUIPMENT TO PASS THE DIFFERENT TYPE OF TEST AS A FUNCTION OF ITS INSULATING CHARACTERISTICS 76

FIG. 18 PROBABILITY P_t OF TEST FAILURE 77

FIG. 19 CUSTOMER'S RISK R_c AS A FUNCTION OF PROBABILITY P_t TO FAIL THE TEST 78

FIG. 20 CUSTOMER'S RISK R_c AS A FUNCTION OF MANUFACTURER'S RISK R_m 79

Indian Standard

APPLICATION GUIDE FOR INSULATION CO-ORDINATION

(First Revision)

0. FOREWORD

0.1 This Indian Standard (First Revision) was adopted by the Indian Standards Institution on 19 April 1978, after the draft finalized by the High Voltage Techniques Sectional Committee had been approved by the Electrotechnical Division Council.

0.2 This standard was first issued in 1966 and covered recommended practices for the co-ordination of the insulation of electrical equipment located in electrically exposed situations. The insulation levels recommended in the 1966 edition were on the basis of IS : 2165-1962*. This revision has been undertaken with a view to bring this guide in line with the latest technological developments taking place in the field of insulation co-ordination like the switching overvoltages. This revision is aligned with the revision of IS : 2165 which has been issued in 1977 wherein proper emphasis on the switching overvoltages has been covered.

0.3 Probabilistic concepts and probabilistic language have also been introduced in this revision for the procedure of insulation co-ordination. This revision acknowledges that the engineers, particularly those who work with extra high voltage field equipment, with the help of powerful computers, are now in a position to make use of such concepts, which afford a better knowledge of system and equipment behaviour and should contribute to a more economical design.

0.3.1 The traditional approach to insulation co-ordination was and still is, to evaluate the highest overvoltage to which an equipment may be submitted at a certain location on a system, and select from a table of standardized values the withstand voltage presenting a suitable safety margin.

Both overvoltage evaluation and safety margin selection are largely empirical and, in many cases, the choice of the insulation level is still more readily based on the previous experience in the system or other similar systems.

---

*Guide for insulation co-ordination.

The object of this standard is not to give strict rules for insulation co-ordination and design, but to provide a guidance toward rational and economic solutions. Therefore, it is intended to consider only a few basic cases, it being evident that stations constituting exceptions to normal design, or included within systems having exceptional characteristics, will require special study by experienced engineers.

0.3.2 In a more elaborate process, it is recognized that overvoltages are random phenomena and that it is uneconomical to design plants with such a high degree of safety that they can sustain the most infrequent ones. It is also acknowledged that tests do not ascertain a withstand level with a 100 percent degree of confidence. In consequence, it is realized that insulation failures can occur occasionally in well-designed plant, and that the problem is to limit their frequency of occurrence to the most economical value, taking into account equipment cost and service continuity. Insulation co-ordination should be more properly based upon an evaluation and limitation of the risk of failure than on the *a priori* choice of a safety margin.

0.4 In accordance with the latest decision taken at the international level, it has been decided to use the term 'surge arrester' in place of 'lightning arrester'.

0.5 In the preparation of this standard assistance has been derived from IEC Pub 71-2 (1976) 'Insulation co-ordination — Part 2 : Application guide' issued by the International Electrotechnical Commission.

0.6 A typical example for 220 kV transformer has been included in Appendix A to make the guide more useful since 220 kV system is more in vogue in our country.

0.7 For the purpose of deciding whether a particular requirement of this standard is complied with, the final value, observed or calculated, expressing the result of a test, shall be rounded off in accordance with IS : 2-1960*. The number of significant places retained in the rounded off value should be the same as that of the specified value in this standard.

1. SCOPE

1.1 This standard provides guidance on the selection of the electric strength of equipment, of surge arresters or protective gaps, and of the most suitable degree of switching overvoltage control. The rated withstand voltages of the equipment are covered in IS : 2165-1977† which forms a necessary adjunct to this standard.

NOTE — This guide is based on apparatus types and ratings in use at present. As new equipment and equipment characteristics are developed and proved, this guide should not be interpreted as a limit to their adoption.

---

*Rules for rounding off numerical values (*revised*).

†Insulation co-ordination (*second revision*).

1.2 This guide covers only phase-to-earth insulation and deals separately with the three following ranges of the highest voltage for equipment:

a) Range A: above 1 and less than 52 kV.

b) Range B: from 52 to less than 300 kV.

c) Range C: 300 kV and above.

1.3 It covers installations of all kinds and in all situations involving voltages higher than 1 kV, whether they are exposed to lightning or not, with the exception of overhead lines. However, the test procedures apply to the latter also.

2. TERMINOLOGY

2.1 For the purpose of this standard the definitions given in IS : 2165-1977* shall apply.

3. VOLTAGE STRESSES IN SERVICE

3.1 General — Dielectric stresses on insulation may be classified as follows:

a) Power-frequency voltages under normal operating conditions,

b) Temporary overvoltages,

c) Switching overvoltages, and

d) Lightning overvoltages.

In IS : 2165-1977*, the overvoltages are classified with reference to the shape of the voltage wave which determines their effect on insulation and on protective devices, without reference to the cause of the overvoltages.

3.1.1 The term 'temporary overvoltages' refers to sustained overvoltages, or to overvoltages having several successive peaks, with a decrement of the amplitude such as to be comparable with a sustained voltage at power frequency or at harmonic frequency.

3.1.2 The term 'lightning or switching overvoltages' refers to overvoltages for which only the highest peak value has to be considered and which can be represented, with regard to their effects on insulation and protective devices, by the steep front standard lightning impulse or the slow front standard switching impulse used for test purpose. The foregoing names have been chosen because such overvoltages often, but not always, originate from lightning discharges or switching operations.

3.1.3 For example, the energization of a transformer-terminated line gives rise to an overvoltage that may be regarded as a switching or temporary overvoltage depending on the decrement of the successive peaks

---

*Insulation co-ordination (*second revision*).

(that is, depending on the circuit constants). As another example, a line-to-earth fault, although actually a switching operation (the same phenomenon would arise if a phase conductor was connected to earth by a circuit-breaker operation) may give rise to steep-front overvoltages, similar to those due to lightning; on the other hand a lightning surge transferred through a transformer by inductive coupling between windings may produce on the secondary side of the transformer long-fronted waves, similar to those due to switching operations.

3.2 Power Frequency Voltages — In insulation co-ordination processes, since overvoltages and impulse voltages are defined in terms of their peak values to earth, it is also convenient to make use of the phase-to-earth peak value of the system voltage, which is $\sqrt{2} / \sqrt{3} = 0{\cdot}816$ times the usual rms phase-to-phase voltage.

Under operating conditions, power-frequency voltage can be expected to vary somewhat in magnitude and may be described by means of a probability distribution about the average operating value. This distribution will differ from one point of the system to another.

For purpose of insulation design and co-ordination, it should, however, be considered as constant and equal to the highest voltage for equipment, which in Range C does not materially differ from the highest system voltage, with a peak phase-to-earth value of $U\text{m}\ \sqrt{2} / \sqrt{3}$. In Range A and in Range B up to 72·5 kV the highest voltage for equipment may be substantially higher than the highest system voltage, as given in **2.3** of IS : 2165-1977*.

For the sake of standardization it is, however, assumed that equipment insulation will always be able to operate satisfactorily at the highest voltage for equipment immediately above, if not equal to, the highest system voltage.

3.3 Temporary Overvoltages — The severity of temporary overvoltages is mainly characterized both by their amplitude and duration.

The importance of temporary overvoltages in insulation co-ordination is twofold:

a) on the one hand the characteristics of temporary overvoltages at the surge arrester location are of great importance in surge arrester selection; and

b) on the other hand, the successive repetition of overvoltage peaks of opposite polarity, even if of lower amplitude than some other overvoltages may determine the design of both the internal insulation of equipment as well as the external insulation (surfaces exposed to contamination).

---

*Insulation co-ordination (*second revision*).

Temporary overvoltages generally arise from:

a) earth faults,

b) load rejection, and

c) resonance and ferro-resonance.

3.3.1 Earth Faults — The overvoltage at power frequency on the sound phases when another phase is accidentally earthed depends, at a given point of the system, on the treatment of the system neutral with respect to earth, as characterized by its earth fault factor at that point.

3.3.1.1 In the evaluation of the earth fault factors the following remarks should be considered:

a) In general, in order to evaluate this factor at a given location, it is assumed for simplicity that the fault is located at the point for which the factor is desired; but, in some special cases, it may be desirable to investigate the effect of other locations on the highest value of the voltage to earth.

b) In principle, there are as many particular values of the earth fault factor at a given location as different possible configurations of the system. The factor which characterizes the location is the highest of the values that correspond to the different system configurations which may occur in practice.

c) The system configurations which have to be considered are those which exist during a fault; thus one should take into consideration those changes in the system which may be produced by the fault itself, for example, on account of the operation of circuit-breakers.

d) For many systems, it will be sufficient to consider only one value of the earth fault factor which covers all the locations on the system.

e) Attention is drawn to the fact that the highest voltage at system frequency which may appear on a sound phase during a particular earth fault does not depend only on the value of the earth fault factor but also on the value of the phase-to-phase voltage at the time of the fault. This phase-to-phase voltage will generally be taken at the highest system voltage, as given in **2.2** of IS : 2165-1977*; but, in some cases, in order to predict the operation of protective devices and specify their characteristics, it is necessary to take into account the increased value of the phase-to-phase voltage that may appear at the selected location under the abnormal conditions not covered by this definition.

---

*Insulation co-ordination (*second revision*).

3.3.1.2 Within Range A and in some cases within range B many systems or installations are operated with their neutral earthed through a high impedance, an arc-suppression coil or with their neutral isolated. For the purpose of insulation co-ordination particular attention shall therefore, be paid in these cases to the earth fault factor.

3.3.1.3 Independently of the earth fault factor particularly high overvoltages may arise in Range A and Range B systems in the case of:

a) earth faults in a system the neutral of which is earthed through an arc-suppression coil when the circuit is under-compensated.

b) arcing earths in a system, the neutral of which is isolated and in many cases in a system the neutral of which is earthed through an arc-suppression coil.

3.3.2 *Sudden Changes in Load* — In the usual conditions of operation the phase-to-phase voltage does not exceed the highest voltage of the system (*see* **2.2** of IS : 2165-1977*); but higher values may temporarily be reached in the case of sudden disconnection of large active and reactive loads; they depend on the system layout after disconnection and on the characteristics of the sources (short-circuit power at the station, speed and voltage regulation of the generators, etc).

This voltage rise may be specially important in case of load rejection at the remote end of a long line (Ferranti effect). It affects mainly the apparatus at the station connected on the line side of the circuit-breaker.

NOTE — From the point of view of overvoltages, a distinction should be made between various types of system layouts. Extreme cases, namely, those with relatively short lines and high value of the short-circuit power at the terminal stations; and those with long lines and reduced value of the short-circuit power at the generating site may be considered. With the latter layouts, as are usual in an extra-high voltage system in its initial stage, much higher overvoltages at system frequency may result when a large load is suddenly disconnected.

Due to the characteristics of the systems, overvoltages of this kind are more severe in voltage Range C than in voltage Range B, overvoltages of this kind, in voltage Range A, may occur in generator transformer-circuits.

3.3.3 *Resonance and Ferro-Resonance* — Temporary overvoltages due to these effects may generally arise when circuits with large capacitive elements (lines, cables, series compensated lines) and inductive elements (transformers, shunt reactors) having non-linear magnetizing characteristics, are energized.

These situations are generally found for systems in Ranges C and B in the following cases:

a) A lightly loaded line, fed or teminated by a transformer may show, for example, harmonic oscillations and pronounced overvoltages if the natural frequency of the linear part of the system corresponds to one of the harmonics of the transformer magnetizing current.

---

*Insulation co-ordination (*second revision*).

b) Subharmonic oscillations and overvoltages may occur in series compensated systems terminated by lightly loaded power transformers or shunt reactors if the impressed voltage, the effective circuit resistance, which is strongly influenced by synchronous machines, and the circuit capacitance fall between certain limits.

c) If harmonic filters are connected to a system containing saturable elements, oscillations due to resonances between these elements and the filter capacitors can develop.

These ferro-resonance effects following energization processes are either stationary or last several cycles of the power frequency being related to the time constant of transformer in-rush currents.

3.3.3.1 Causes of resonance and ferro-resonance in voltage Range A are:

a) resonance between inductive and capacitive components, for example, when capacitors for power-factor correction are used.

b) ferro-resonance which may occur when a transformer whose secondary is loaded by a small capacitance only, is switched in or out, with an appreciable time between operations on each phase.

c) ferro-resonance which may occur where there is an iron-cored inductive load such as a voltage transformer already connected or being switched in.

3.4 Switching and Lightning Overvoltages

3.4.1 For the purpose of this guide switching overvoltages are, as stated above, of a type which may be simulated by a standard switching impulse, that is, an aperiodic wave with a front duration of the order of hundreds of microseconds and a tail of the order of thousands of microseconds. They stress the various parts of an insulation in about the same proportions as power-frequency voltages but are not repetitive and only one peak of either polarity is normally significant.

3.4.2 Lightning overvoltages are those which may be simulated by a standard lightning impulse, that is, an aperiodic wave with a front duration of the order of one microsecond and a tail duration of the order of several tens of microseconds. Due to the front steepness they stress more than the former the longitudinal insulation of inductive windings, and because of their shorter duration, generally a somewhat higher stress may be withstood by a given insulation.

3.4.3 These overvoltages generally arise from:

a) line energization and re-energization,

b) faults and fault clearing,

c) switching of capacitive currents and of small or moderate inductive currents,

d) load rejection, and

e) lightning strokes (first or subsequent components of a lightning flash).

NOTE — The overvoltages in cases (a) to (d) depend on the characteristics of the equipment, especially of the circuit-breakers, transformers and reactors. They may generally be reduced by suitable choice of the characteristics/that is, in case (a) for example, by using pre-insertion resistors or reactors and in case (c) the overvoltage may be reduced by surge arresters connected between the circuit-breaker and the transformer.

3.4.3.1 *Line energization and re-energization overvoltages* — Overvoltages due to closing, and to single and three-phase reclosing are of great importance in the selection of system insulation in Range C. In this voltage range, restrike-free breakers are in general use.

Overvoltages due to line energization and re-energization are not of particular importance in the other ranges of voltages.

3.4.3.2 *Switching overvoltages due to faults and fault clearing* — In Range A and, in relatively few cases, in Range B under the conditions listed in items (a) and (b) in **3.3.1.3** high switching overvoltages can arise at the initiation of a fault.

In all the voltage ranges, high overvoltages may arise due to faults to earth in composite circuits (overhead lines and cables as transformer terminated feeders).

At the highest voltages of Range C a high degree of control of overvoltages caused by line energization and re-energization is normally attempted. For this reason switching overvoltages due to faults and fault clearing (single and double line-to-earth faults and their clearance) need careful consideration.

3.4.3.3 *Overvoltages due to switching of inductive and capacitive currents* — In Range A the switching of inductive or capacitive currents may give rise to overvoltages, which may require attention, both in high voltage distribution systems and in industrial installations and power stations. In the case of the former, high overvoltages may arise if the circuit-breaker deionizes so rapidly as to force the current prematurely to zero, so-called current chopping.

In particular the following switching operations are to be taken into consideration:

a) Interruption of the starting currents of motors;

b) Interruption of inductive current, for example, when interrupting the magnetizing current of a transformer or reactor;

c) Switching and operation of arc furnaces and their transformers which may lead to current chopping;

d) Switching of unloaded cables and capacitor banks; and

e) Interruption of currents by high-voltage fuses.

In Range B overvoltages due to the interruption of capacitive currents (switching off unloaded lines, cables or capacitor banks) may be particularly dangerous since the use of restrike-free breakers may not alway be assumed.

3.4.3.4 *Load rejection* — Overvoltages due to load rejection may start with a high switching surge followed by a temporary overvoltage.

Overvoltages of this kind are particularly important in Rang C at the highest voltages where a high degree of control of reclosing surges is attempted.

3.4.3.5 *Lightning overvoltages* — Lightning overvoltages are caused either by direct strokes to the phase conductors, back-flashovers, or as a result of earth flashes in the proximity of the line which produce indirect lightning surges. The overvoltages by which substation insulation is stressed are a function of the line construction and the system configuration. The configuration of the station itself has a great influence if the travelling time of surges within the station is not negligible in relation to the front time of the surge.

Depending on the system configuration, overvoltages with time parameters in the range of switching surges may also arise as a result of lightning strokes.

Lightning discharges which produce significant overvoltages, in Range B and C, are confined to direct strokes to phase conductors or strokes to towers or earth wires with subsequent back-flashovers.

In Range A indirect lightning surges shall also be considered. Furthermore in this range surges transferred through transformers from a higher voltage system need careful consideration.

3.5 Determination of the Expected Overvoltage Level

3.5.1 *Range A* — For voltages of less than 52 kV switching overvoltages constitute generally no serious problem for overhead supply systems and insulation co-ordination is based on lightning overvoltages.

Switching overvoltages transferred from an overhead line into a plant through transformers or lengths of cable may, in general, be ignored for the same reason. An exception is the case of an installation connected to the lower-voltage side of a high-voltage transformer feeder, particularly if resonance occurs between the two systems during one or two-phase energizing.

In industrial plants and power stations, the amplitudes and waveshapes of switching overvoltages generated within the installation vary over a very wide range. In the great majority of cases they are innocuous; in some, serious overvoltage magnitudes and rates of change may occur. Thus sudden voltage swings may be caused when a switching device re-strikes; the resulting rate-of-change of voltage may equal that caused by a severe close lightning strike.

A very large amount of practical operational experience is available from different industrial plants and power stations and the most severe overvoltages or voltage swings may usually be avoided by eliminating resonance and by the correct choice of switching device to be employed.

Detailed representation of the system under consideration on the digital computer or on the TNA may not be economically justified at this voltage level since accurate representation is needed to obtain accurate results and a complex plant frequently consists of many pieces of equipment and electrical connections. Furthermore the operation of some types of switching device and arcing earths are difficult to simulate with a sufficient degree of accuracy. Experience is often the best guide and in exceptional cases, deliberate switching tests with simultaneous recording (both high-speed and low-speed) will produce the most valuable information so that remedial measures may be taken as the result of subsequent calculations and confirmatory tests.

The amplitudes, waveshapes and frequency of occurrence of lightning overvoltages on systems in Range A may be estimated with a reasonable degree of accuracy. As the impulse flashover voltage of insulators used on overhead lines in this range is quite low as compared with the potential impressed on such a line by a direct lightning stroke, the stresses to which substation equipment is liable to be subjected are primarily determined by the type of line construction. Thus careful protection of substation equipment is required if this is connected to a wood-pole line with unearthed crossarms. Reduced protection is needed where the lines are erected on steel masts, reinforced concrete poles or where metal crossarms are otherwise earthed.

Apart from this important difference, the amplitude and waveshapes are affected by the following factors which characterize the constitution of the system and arrangement of the station.

3.5.1.1 *Surge impedance of those lines or cables which are connected to the station* — For example, when only one line is connected to a terminal transformer the surge is reflected at the termination and is doubled in voltage amplitude; when n lines of the same surge impedance are connected to the busbars of a station and if no lightning stroke to the line occurs near the station, the voltage at the busbars becomes $2\ u/n$, where u is the amplitude of the surge voltage transmitted along the line on which the lightning surge originated.

3.5.1.2 *Cables with an earthed metallic sheath in series with the line or connected between the station busbars and apparatus to be protected* — A short cable mainly reduces the steepness of most of the waves entering the station; a cable of one or a few kilometres length may also reduce the surge amplitude. In the case of a direct lightning stroke to the last span in front of a station, a cable section between overhead line and station affords practically no relief to the station equipment.

3.5.1.3 *Protective earth wires on the overhead lines extending up to a few kilometres ahead of the station* — These are effective against close lightning strikes to the line which are the most dangerous. This presupposes that shielding by the earth wires is sufficiently well designed to prevent direct strokes reaching the phase conductors, and that the earthing resistance of the tower is sufficiently low to reduce the risk of back flashover, for example, 10 ohms for a 36 kV line.

3.5.1.4 *Protective spark gaps or protective earth wires extending over one or two spans in front of the station* — These may materially reduce the amplitudes of incoming surges on lines with high insulation to earth, for example, on fully insulated wood-pole lines.

3.5.1.5 *Earthing resistances and inductances of the down leads of towers, particularly close to the station* — In the cases of high values of earthing resistance or the inductance of the down lead of the tower or pole, a lightning strike to such a tower or pole or to an earth wire may cause high overvoltages on the phase conductors by back flashover across the line insulators to one or more phase conductors.

3.5.1.6 In Range A lightning surges transferred through transformer. are also important. Analytical expressions for the electrostatic and electromagnetic terms of the transferred voltage are derived in Appendix A.

3.5.2 *Range B* — In this range of voltages also the insulation levels are generally such that switching overvoltages are seldom a major problem and that insulation co-ordination is still mainly based upon lightning overvoltages in overhead line systems.

Furthermore, also in this voltage range, there is usually no decisive economic incentive towards a detailed study of overvoltage stresses.

Thus the considerations in **3.5.1** also apply to Range B.

3.5.3 *Range C* — Although a switching impulse test has been substituted in this range, as more realistic, for the traditional one minute power frequency test, it is only for the highest values of the range that switching overvoltages become the predominant factor in insulation co-ordination.

The high cost of equipment then compels consideration of less liberal designs of insulation co-ordination, while, in turn, the serious consequences of a failure necessitate a more precise estimation of the overvoltages to be expected. These have to be evaluated for each type of significant overvoltage in the particular system considered.

Because of the extensive computational requirements, virtually all practical overvoltage predictions must be made using transient network analyzers or digital computers.

Experience with studies of a wide variety of systems has shown that development of generalized formulae for expected overvoltages is difficult because of the large number of parameters affecting the overvoltage value.

Both analogue and digital techniques of transient solution require a reasonably high level of skill in problem-solving. These skills are principally useful in the selection of significant cases (it being impractical to study all possibilities), in the reduction of the system to a reasonable number of busbars and lines (it is not practical to represent the entire system on either TNA or digital solutions) and in the description of system constants and apparatus characteristics.

Whenever possible, field tests to check the validity of the parameters used are recommended.

In the sophisticated approaches to insulation coordination now which are increasingly used for the highest values of voltage, the amplitudes of the overvoltages to be expected at a given location due to a given type of event, may not be defined by a single value (*see* Fig. 1). It is only possible to state what is the probability $f_o\,(U)\, dU$ that an overvoltage value comprised between U and $U + dU$ may occur, $f_o\,(U)$ being the overvoltage probability density. The probability $F_o\,(U')$ that the value U' may be exceeded is then given by:

$$F_o(U') = \int_{U'}^{\infty} f_o(U)\, dU \text{ ' } for \text{ ' } F_o(U') = \int_{u'}^{\infty} f_o(U)\, dU \qquad \ldots(1)$$

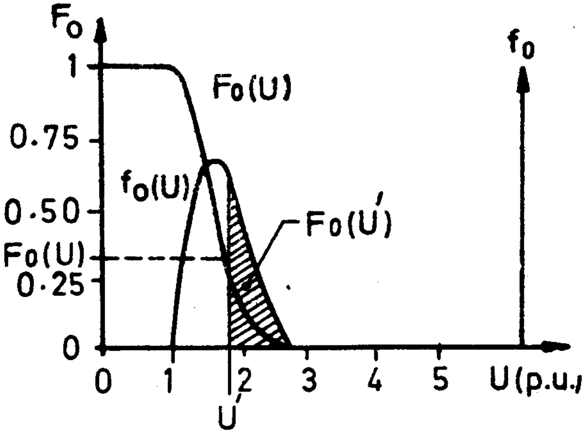
4. INSULATION WITHSTAND

4.1 General

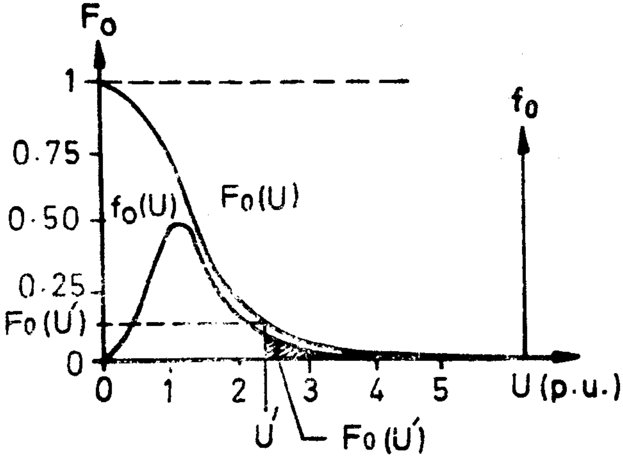
4.1.1 *Self-Restoring and Non-Self-Restoring Insulation* — Clauses **2.8** and **2.9** of IS : 2165 - 1977* subdivide insulation into self-restoring and non-self-restoring insulation according to its behaviour in case of the occurrence of a disruptive discharge during a dielectric test. On the former kind of insulation it is possible to carry out tests under conditions that imply an appreciable risk of such discharges, for example, by applying a large number of impulses at the rated impulse withstand voltage, or even in conditions with deliberately applied discharges as in a 50-percent disruptive discharge test carried out at voltages above the rated impulse withstand level.

---

*Insulation co-ordination (*second revision*).



1A Line Energization Overvoltages



1B Overvoltages Across an Insulator String Due to Lightning Strokes to the Tower

f_o (U) = overvoltage probability density

F_o (U) = overvoltage (cumulative) probability

FIG. 1 OVERVOLTAGES

On non-self-restoring insulation a disruptive discharge destroys the insulating property of the insulation and a large number of impulses at rated withstand voltage may result in a gradual deterioration of the insulation. Non-self-restoring insulation is for these reasons tested by application of a limited number of impulses at rated withstand voltage.

The degree of information on the dielectric strength of the equipment directly obtainable may thus be much higher for self-restoring insulation. However, in the case of non-self-restoring insulation, the economic importance for the manufacturer of the risk of having the equipment rejected tends to oblige him to design the equipment for a very low probability of failure under test. Taking these two factors together, no difference is made in IS : 2165 - 1977* between impulse withstand levels, in relation to the kind of insulation or the nature of the test.

While self-restoring insulation does not lose or modify its insulating ability following a disruptive discharge in a dielectric test, it should not be inferred that damage may not occur in service if the disruptive discharge is followed by an intense power arc.

Furthermore, possible damage to equipment is not the only consideration to be introduced in the selection of an acceptable risk of discharge in service, as the effect on continuity of supply also has to be considered. For example, a much lower probability of insulation failure is required in the case of bus-bars than on individual lines.

It shall be emphasized that the insulating structures of a piece of equipment are always made up of self-restoring and non-self-restoring parts. Generally it may not, therefore, be stated that the insulation of an apparatus is self-restoring or non-self-restoring. But the probability that discharges may occur across or through non-self-restoring parts in the presence of self-restoring parts may, for different types of equipment, be negligible or not. Due to the different voltage-time discharge characteristics of solid and air insulations, this probability tends to increase with increasing impulse voltage amplitudes: thus it may be negligible at the rated withstand voltage but may become appreciable around the 50 percent disruptive discharge voltage.

4.1.2 *Selection of the Type of Test* — For some types of apparatus, within the range of overvoltages that tests have to simulate, the probability that a discharge occurs across a non-self-restoring part is negligible. In this case the discharge probability coincides with that of the self-restoring parts of the apparatus and its insulation may be called essentially self-restoring; or, for the sake of simplicity, self-restoring. Disconnecting switches may be considered an example of this type; in fact even when applying impulses well above the 50 percent discharge voltage during a 50 percent discharge test, sparkover takes place usually in air without any puncture of the porce-

---

*Insulation co-ordination (*second revision*).

lain. For this type of equipment the test given in **7.3** of IS : 2165-1977* is possible and recommended.

Insulation of other pieces of equipment, for instance bushings, behaves like self-restoring insulation up to the rated impulse withstand voltage level, but this implies an overinsulation of the non-self-restoring parts as compared with the self-restoring ones, and this overinsulation, although economically permissible, has to be limited to an acceptable extent. Thus, above this value a non-negligible probability exists that discharge takes place on non-self-restoring parts. Insulation of this type of equipment, that could be called combined, should be tested according to **7.4** of IS : 2165-1977*.

Finally, the cost of the non-self-restoring parts of some equipment, for instance power transformers, may be so high as to make overinsulation unacceptable. Insulation of this kind of equipment is called essentially non-self-restoring or, for the sake of simplicity, non-self-restoring. This kind of insulation is verified by means of the test described in **7.5** of IS : 2165-1977*.

Considerations on the validity of the above tests are given in Appendix B.

4.2 Insulation Behaviour at Power-Frequency Voltage and Temporary Overvoltages—In general, discharge under power-frequency voltage in normal operating conditions and under temporary overvoltages will be caused by progressive deterioration of the insulating properties of the equipment or by exceptional reductions in insulation withstand due to severe ambient conditions.

In the latter case, the concept of probability is applicable to the degree of contamination (*see* **3.2**).

Because of the difficulties involved, no use of statistical concepts will be made in these specifications in respect of insulation behaviour at power-frequency voltage and temporary overvoltages (*see* also **6.1** and **6.2**).

4.3 Probability of Discharge of Insulation Under Impulse Voltages—The ability of a given insulation to withstand the dielectric stresses caused by the application of an impulse of given waveshape and peak value U is, in most cases, a random phenomenon, even if we consider a time interval so small (such as that needed to carry out a dielectric test on equipment) that the ambient and insulation conditions may be considered constant, at least in respect of quantities such as pressure, temperature, humidity, etc, which may be measured and which are used to define the ambient and insulation conditions during tests.

The discharge probability of an insulation to an impulse of given waveshape and polarity, and to a peak value U in a short time interval as

---

*Insulation co-ordination (*second revision*).

defined above (for example, in a dielectric test) may be determined, if the insulation is self-restoring, by applying the impulse U 'N' times within this time interval, and counting the number 'n' of discharges. From the value $\frac{'n'}{N}$ a numerical value may be obtained for this probability which will be the more accurate the greater the value is of 'N'.

Determination of the discharge probability of a given piece of non-self-restoring insulation caused by the application of a very small number of voltage impulses of given waveshape and peak value U, which shall be withstood without any failure is, obviously not possible; but this should not prevent us from regarding it as existing in theory and studies are continuing on the probability aspect of non-self-restoring insulation failure.

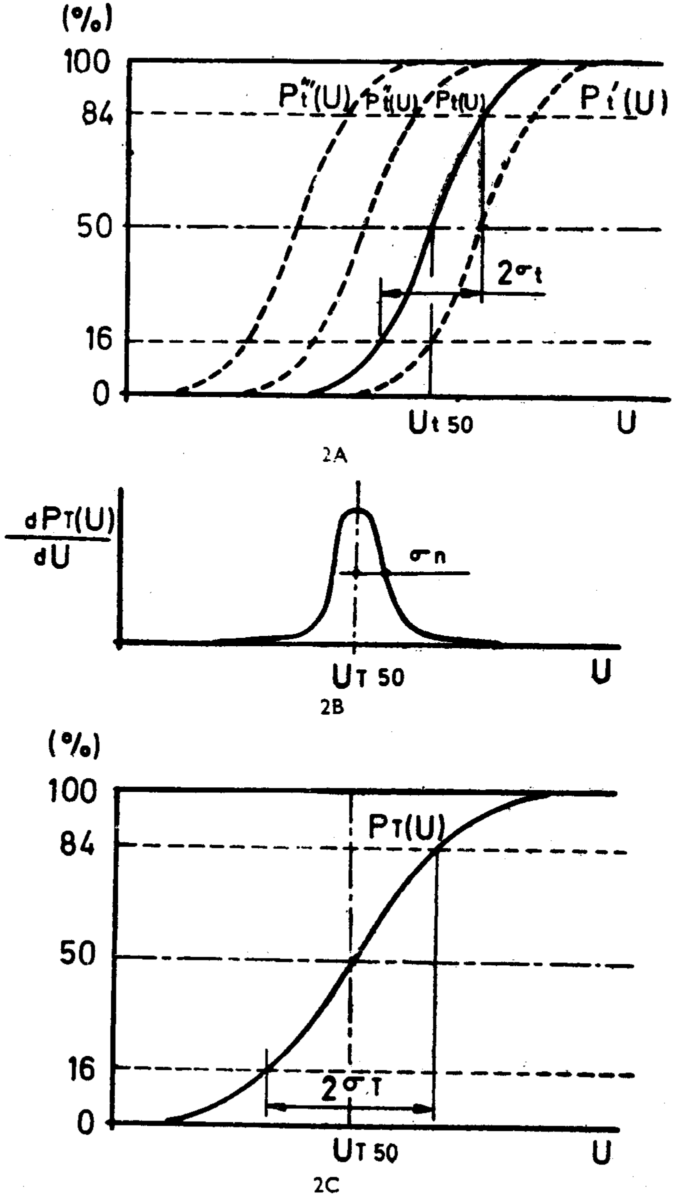
If we consider either switching or lightning impulses of different peak values U, we shall be able to associate with every possible value of U a discharge probability P_t, thus establishing a relationship P_t (U) for a given insulation in a short time interval Δt or for the sake of simplicity at a time t (*see* Fig. 2A).

The values of P_t (U) increase from near 0 to near 100 percent probability in a more or less narrow band of voltage values. In general the resulting curve may be defined by a biparametric law, one parameter being associated with the position of the band and giving an indication of the withstand level, and the other associated with the bandwidth and giving an indication of the scattering of the voltage values which give appreciable proportions of both discharges and non-discharges.

Generally in a laboratory the parameter that defines the position of the probability curve is taken as the voltage U_{t50} which corresponds to the 50 percent discharge (withstand) probability. The standard deviation of the distribution (σ_t), which corresponds to half the difference between the voltages that give discharge probabilities of 16 percent and 84 percent, is usually taken as the parameter which expresses the scattering.

In the service the ambient and insulation conditions do not remain constant. Therefore, the discharge probability curve of insulation, as defind above for the time t, is bound to change from one moment to another ($P_{t'}$, $P_{t''}$......) (*see* Fig. 2A). The variations are determined, as regards external insulation, mainly by atmospheric conditions.

Taking the ambient and insulation conditions as random, it will be necessary to consider for each insulation, in addition to the discharge probability P_t (U), as defined above, also a discharge probability of insulation P_T (U) to overvoltages of amplitude U liable to occur at any instant of a long time interval T of operation. For the purpose of insulation design, it is this second distribution which is of interest to the engineer (*see* Fig. 2C).



2A

2B

2C

FIG. 2 PROBABILITY OF DISRUPTIVE DISCHARGE (FOR GAUSSIAN DISTRIBUTION) OF INSULATION UNDER IMPULSE VOLTAGE

Similarly to $P_t(U)$, $P_T(U)$ may be defined by the voltage U_{T50} which corresponds to the 50 percent discharge (withstand) probability and by the standard deviation σ_T of the distribution.

The variations of $P_t(U)$ within the time interval ΔT may be conveniently defined by the probability density P_n which is a function of U_{t50} taken as a random variable (*see* Fig. 2B). This latter function in turn may be characterized by the 50 percent discharge voltage U_{T50} and by its standard deviation σ_n.

On the simplifying assumption that the standard deviation σ_t of $P_t(U)$ is constant within the time interval Δ_T, the following relation holds:

$$\sigma_T = \sqrt{\sigma_t^2 + \sigma_n^2} \qquad \text{.. (2)}$$

In clause **2.22** of IS : 2165-1977* the parameter that defines the position of the probability curves $P(U)$ is taken as the voltage which corresponds to a withstand probability of 90 percent although the 50 percent discharge voltage which was referred to above is a convenient measure for pieces of insulation that may be submitted to a 50 percent disruptive discharge tests.

The reason for this choice is that the 50 percent disruptive discharge test may not generally be applied to all kinds of insulation. Thus, in order to have the same value of the rated impulse withstand voltages for all types of equipment, whatever its insulation, and to use these values directly in the definitions of the statistical distributions, it has been deemed appropriate to refer to a higher value (90 percent) of the withstand probability, the rated impulse withstand voltage U_{RW} being identical with the lowest permissible value of the statistical impulse withstand voltage under specified test conditions (U_{t90}).

For risk-of-failure evaluations it is, however, convenient to express the probability curves of insulation discharge in terms of their 50 percent discharge voltages and standard deviations.

Assuming for $P_t(U)$ a Gaussian distribution with standard deviation σ_t, the difference between the 50 percent discharge (withstand) voltage and the statistical or 90 percent withstand voltage is given by:

$$U_{t50} = \frac{U_{t90}}{1 - 1{\cdot}3\,\sigma_t} \qquad \text{... (3)}$$

σ_t is taken as 0·03 or 0·06 depending on the type of impulse, lightning or switching, unless another value has been specified for the relevant equipment (*see* **7.3** of IS : 2165-1977*).

The probability of discharge $P_t(U)$ of a piece of equipment which during the test is conforming to what is specified in IS : 2165-1977* may

---

*Insulation co-ordination (*second revision*).

then be defined in terms of its 50 percent discharge voltage and its standard deviation, as follows:

$$U_{t50} = \frac{U_{t90}}{1 - 1{\cdot}3\,\sigma_t} > \frac{U_{RW}}{1 - 1{\cdot}3\,\sigma_t} \qquad \dots (4)$$

The $P_t(U)$, defined by the above parameters, refers to the most severe test conditions for the equipment, since U_{RW} is the rated switching or lightning impulse withstand voltage. Therefore, if impulse tests have to be made with the equipment both dry and wet, $P_t(U)$ refers generally to the wet conditions.

The probability of discharge in service $P_T(U)$ of a given piece of equipment may be deduced from field tests only, depending on the site of installation.

However, as a broad indication the $P_T(U)$ of a piece of equipment conforming to what is specified in IS : 2165-1977* may be defined, recalling equation 2, in terms of its 50 percent discharge voltage and its standard deviation, as follows:

$$U_{T50} > k\,\frac{U_{RW}}{1 - 1{\cdot}3\,\sigma_T}$$

$$\sigma_T = \sqrt{\sigma_t^2 + \sigma_n^2} \qquad (5)$$

where k is the ratio between the 50 percent discharge voltage of a given equipment in service during a time interval Δ_T and the 50 percent discharge voltage under the most severe impulse test for the equipment (wet or dry, positive or negative polarity).

For switching impulses U of positive polarity, the values of k and σ_n relevant to time intervals Δ_T of fine dry weather or various bad weather conditions do not show appreciable differences. The same may be said concerning the degree of ambient pollution, at least in the range from clean conditions to lightly polluted conditions.

For switching impulses U of negative polarity, the values of k and σ_n are highly dependent on the type of weather within the time interval Δ_T under consideration. Concomitance of bad weather (rain, snow, fog, mist etc) and not negligible pollution leads to a low value of k; bad weather also increases the value of σ_n.

Values of $k = 1$ and $\sigma_n = 5$ percent are suggested in these recommendations for normal conditions and a time interval Δ_T equal to the seasonal cycle to cover the worst polarity impulse. This value of σ_n results in a value of σ_T a little lower than 8 percent.

---

*Insulation co-ordination (*second revision*).

The same values of k and σ_n are also suggested for lightning impulses. This gives a value of σ_T equal to 6 percent approximately.

The information given above is to be considered merely as broadly indicative and it is recommended that use shall be made of more detailed data derived from field tests if available.

4.4 Equipment with Windings — An equipment with high-voltage windings, such as a transformer or reactor designed to withstand only full-wave tests, is vulnerable to a certain extent to a surge of high amplitude chopped in its vicinity, because higher internal stresses than under full-wave conditions may be developed across adjacent turns and coils. All flashovers to earth in a substation result in chopped waves of various degree of amplitude and steepness. If because of the use of protective spark gaps these are liable to occur frequently in service the strength of the windings against surges shall be determined by testing with a suitable chopped wave. The provision for such a test is left to the relevant equipment specification.

Where non-linear resistor-type surge arresters are used for the protection of transformers, chopped waves are less likely to arise and chopped wave tests are usually not required.

For all types of apparatus having windings, such as rotating machines, transformers and reactors, rapidly changing voltages due to the restriking of switching devices may also produce non-linear voltage distributions similar to those caused by lightning overvoltages. For this reason, it is recommended that such equipment, irrespective of whether or not it is to be used in installations subjected to lightning overvoltages, should be tested with a lightning-impulse voltage to check the winding insulation for voltage withstand across turns and coils.

5. PROTECTIVE DEVICES

5.1 General — These devices fall under three classes:

a) non-linear resistor-type surge arresters;

b) expulsion-type surge arresters (Range A only); and

c) spark gaps.

The choice between these three devices, which do not provide the same degree of protection, depends on various factors, for example, the importance of the equipment to be protected, the consequences of an interruption of service, etc.

In the following clauses, their characteristics will be considered from the point of view of insulation co-ordination.

5.2 Non-linear Resistor-Type Surge Arresters — These protective devices should be designed and installed to limit the magnitudes of overvoltages against which they have to protect equipment so that the total surge-arrester voltage during operation does not exceed an acceptable value. They are defined and their characteristics are given in IS : 3070 (Part I)-1974*. Their rating is defined as the designated maximum permissible rms value of power-frequency voltage between their terminals at which they are designed to operate correctly; this voltage may be applied to surge arresters continuously without changing their operating characteristics. In addition to this defined capability, some types of surge arresters† may successfully withstand either (a) higher than rated voltage for a specified short duration or (b) a specified number of successive discharges.

In either case a controlling factor in the selection of the surge arrester is its ability to interrupt power follow current at either the rated voltage or at the higher temporary overvoltages.

A primary point is that the total voltage produced across the terminals of the arrester at any moment during operation shall be considered in the determination of the switching impulse protective level and the lightning impulse protective level.

5.2.1 *Lightning Impulse Protective Level* — The lightning impulse protective level of a surge arrester is characterized by the following voltages:

a) The sparkover voltage for a standard full lightning impulse wave [*see* Table 3 of IS : 3070 (Part I)-1974*];

b) The residual (discharge) voltage at the selected standard nominal current [*see* Table 4 of IS : 3070 (Part I)-1974*]; and

c) The front-of-wave sparkover voltage [*see* Table 3 of IS : 3070 (Part I)-1974*].

NOTE — The tables mentioned here give for each surge arrester voltage rating the upper limit for each of the above voltages. If better characteristics than those specified in IS : 3070 (Part I)-1974* are available, the actual voltages for the specific surge arrester will be obtainable from the manufacturer. Thus, it is recommended that the actual voltages for the surge arrester protective characteristics be used for co-ordination studies.

The protective level under lightning impulses is taken for insulation co-ordination purposes as the highest value among either (a), (b) or (c) divided by 1·15 (*see* **2.29** of IS : 2165-1977‡). This evaluation of the protective level gives a conventional value representing a generally acceptable approximation. For a better definition of wave-front protection by a surge arrester, reference should be made to IS : 3070 (Part I)-1974*.

---

*Specification for lightning arresters for alternating current systems : Part I Non-linear resistor type lightning arresters (*first revision*).

†These special types of surge arresters are at present applicable to Range C only.

‡Insulation co-ordination (*second revision*).

5.2.2 *Switching Impulse Protective Level* — The switching impulse protective level of a surge arrester is characterized by the following voltages:

a) The maximum sparkover voltage for the standard impulse shapes specified in **7.7.4** of IS : 3070 (Part I)-1974*; and

b) The total surge arrester voltage exhibited by the surge arrester when discharging switching surges.

The protective level for switching impulses is the higher value of (a) or (b). Until a standard test for (b) is devised, reference should be made to the surge arrester manufacturer.

5.3 Expulsion-Type Surge Arresters — These protective devices operate to limit overvoltages and interrupt follow currents within their rating. They have low residual voltages. The characteristics of these devices are given in IS : 3070 (Part II)-1966†.

The impulse sparkover characteristics resemble those of protective spark gaps but are in general lower and flatter for the same sparkover distance.

These arresters may not appreciably limit the amplitude of the follow current before interrupting it and may have current-interrupting ratings which must be compared with the prospective fault current and the prospective transient recovery voltage at the point of installation.

5.4 Spark Gaps — The spark gap is a surge protective device which consists of an open air gap between an energized electrode and an earth electrode.

On supply systems operating at voltages up to 245 kV spark gaps have proved satisfactory in practice in some countries with moderate lightning activity. The adjustment of the gap settings shall often be a compromise between perfect protection and service continuity but this difficulty may be largely overcome by the use of rapid automatic reclosing.

The sparkover voltage and the time-to-sparkover of the gap depends essentially on the distance between the electrodes; they are influenced by the shape of the electrodes and also by their disposition and distance relative to the neighbouring live and earthed parts.

In order to improve the operation of a spark gap under steep-fronted surges and to provide a flatter impulse sparkover-voltage time characteristic, the geometrical configuration of the simple rod to rod electrode arrangement may be modified, for instance by appropriate shaping of the electrodes and

---

*Specification for lightning arresters for alternating current systems : Part I Non-linear resistor type lightning arresters (*first revision*).

†Specification for lightning arresters for alternating current systems : Part II Expulsion type lightning arresters.

by provision of a central auxiliary electrode. In Range A duplex-type gaps have also proved advantageous in regions where birds or small animals are troublesome.

5.4.1 *Protective Characteristics of a Spark Gap* — The protection obtained by means of spark gaps is less precise and the protective level may not be given as precisely as the protective level of non-linear surge arresters for the following reasons:

a) The dispersion of the sparkover voltage of a gap; and
b) The increase in the sparkover voltage with increasing amplitude of the applied wave when sparkover takes place on the front of the wave.

The performance of a gap under impulse (switching or lightning) is characterized by the 50 percent value and the standard deviation of its discharge voltage under standard laboratory conditions. Since spark gaps constitute typical self-restoring insulation, the contents of **4.3** apply to them as well. Furthermore, because of the reasons given in item (b) above, knowledge of the times-to-sparkover of the gap for values of the applied impulses well above the 50 percent sparkover value is often needed (*see* Appendix C).

5.4.2 *Limitations of Protective Gaps*

5.4.2.1 When the gap operates on a voltage surge and a power-arc results, it frequently persists until disconnected by a fault protective device; this constitutes a short-circuit in the case of a system with directly earthed neutral, entails mechanical stresses on the various parts of the system equipment and may cause disturbances to consumers. The location of the gap should therefore, be considered in relation to its effect on the system protection and operation.

5.4.2.2 The gap is unacceptable from the point of view of service countinuity if its presence noticeably increases the number of circuit outages provided these flashovers are neither self-extinguishing nor interrupted by means of high-speed tripping followed by high-speed reclosing.

5.4.2.3 Spark gap operation causes chopping of the wave, thus increasing the probability of producing chopped waves close to the terminals of protected apparatus. This has to be taken into consideration for insulation of high voltage windings (*see* **4.4**).

5.4.2.4 Damage to the apparatus may be caused by the power arc across the gap if this is not installed in a suitable position. For instance if a spark gap is fitted to a bushing, for example, of a transformer or circuit-breaker, its distance from the bushing surface shall be sufficiently large to prevent a power arc being blown against the insulator,

5.5 Application of Different Protective Devices

5.5.1 *Protection with Non-linear Resistor-Type Surge Arresters* — In order to ensure that an apparatus is not subjected to a surge voltage exceeding that which appears across a surge arrester, it is a general rule to locate the arrester as close as possible to the apparatus. In particular, surge arresters should preferably be either installed on the transformer tank or its high-voltage and earth terminals should be connected to the transformer by the shortest possible connections.

Similarly surge arresters should be fitted close to cable terminations, if they need protection, with the shortest possible connections between the terminals of the surge arrester and the phase conductor and the cable sheath respectively.

NOTE — In the case of surge arresters close to the apparatus to be protected the following conventional safety factors are recommended:

a) *Range A* — A safety factor of approximately 1·4 should be provided between the rated lightning impulse withstand level of the apparatus to be protected and the impulse protective level of the surge arrester.

b) *Ranges B and C* — Conventional safety factors of 1·2 - 1·4 are normally provided for lightning overvoltages.

c) *Range C* — Conventional safety factors of 1·1 - 1·2 are normally provided for switching overvoltages.

The considerations in IS : 4004-1978* shall also be taken into account.

The installation of surge arresters close to the apparatus to be protected may be achieved more easily in Range A than in Ranges B and C.

When the surge arrester is separated from the apparatus to be protected the apparatus is subjected to a surge voltage which exceeds the protective level of the arrester. The excess voltage is due firstly to the inductive voltage drop in the connecting leads of the arrester itself and those connecting it to the apparatus to be protected. Secondly, if the time of surge propagation between arrester and apparatus is not negligible compared with the front duration of the incoming surge, the effect is a short-time increase of the voltage at the terminals of the apparatus to be protected over the protective level of the surge arrester.

The increase due to both these factors depends on a number of conditions, namely, distance of the surge arrester and its location ahead of, or behind, the apparatus to be protected; characteristics of the line; capacitance of the apparatus to be protected; arrangement of the station and steepness of the incoming wave. This increase may be limited by all arrangements which limit the steepness of the surge arriving at the station

---

*Application guide for non-linear resistor-type surge arresters for alternating current systems (*second revision*).

[extension of shielding wires, localized capacitance, cable (even short), large number of connected lines]. The adoption of a reduced protective level is another help.

5.5.2 *Protection with Expulsion-Type Surge Arresters* — These arresters are sometimes used on high-voltage distribution circuits where shielding against lightning is not provided (Range A).

The impulse sparkover voltage time characteristics of such an arrester is flatter than that of a rod gap of the same sparkover distance, but not quite as flat as that of some type of equipment, for example, a transformer winding or a cable.

For this reason, an adequate margin of safety is required, not only for the lightning impulse sparkover voltage of the arrester and of the equipment to be protected but also for the corresponding front-of-wave sparkover voltage. These conditions are assisted by the usual practice of installing these types of diverter close to the equipment to be protected.

For further specification concerning the applications of these devices, reference should be made to IS : 3070 (Part II)-1966*.

5.5.3 *Protection with Spark Gaps* — The impulse sparkover voltage-time curve of a spark gap is usually much more curved than those of some of the types of apparatus to be protected, particularly those of transformers and cables.

Due to the curved shape of the voltage-time characteristic of a spark gap, the distance over which protection is given for all surges is very small, usually not more than a few metres. If a spark gap is applied for protection against surges of a limited front steepness (considerably lower than the steepness of the standard lightning-impulse test voltage wave), a distance of several tens of metres between the gap and the object to be protected does not appreciably modify the conditions for the protection provided against such surges.

A spark gap is, therefore, liable to operate not infrequently when stressed by lightning surges, and occasionally when stressed by switching surges, the amplitudes of which are below the lightning-impulse withstand voltages of the apparatus to be protected. In a large number of cases the operation of the spark gap causes a circuit outage if the gap is on the supply side of the opening switch. If the supply may be restored quickly by high-speed automatic reclosing the setting of the spark gap may be so adjusted as to provide an acceptable degree of protection to the apparatus without causing an excessive number of troublesome supply interruptions to consumers.

NOTE — Safety factors of the order of those given for surge arresters secure generally satisfactory protection provided the occurrence of very steep fronted surges is excluded (Appendix C).

---

*Specification for lightning arresters for alternating current systems : Part II Expulsion type lightning arresters.

6. CO-ORDINATION BETWEEN STRESSES AND WITHSTAND CONSIDERATIONS COMMON TO RANGES A, B and C

6.1 Insulation Design to Power Frequency Operating Voltage and Temporary Overvoltages — Problems of Pollution and Ageing — In 3.4 and 3.5 of IS : 2165-1977* it has been specified that the relevant equipment specification shall prescribe the long duration power-frequency tests intended to demonstrate the behaviour of equipment with respect to internal insulation ageing or to external pollution. Only general guidance is given to the equipment committees; it is indicated that as regards the voltage under normal operating conditions, the insulation shall withstand permanent operation at the highest voltage for equipment.

6.2 Pollution

6.2.1 For insulation susceptible to contamination, the problem of specifying a suitable test method and pollution severity levels is at present under consideration for various relevant equipment specifications. When contamination tests are established, it is anticipated that the system engineer will specify a degree of pollution severity level in relation to the pollution of the ambient in which the equipment is installed.

6.2.2 Table 1 gives a provisional basis to the system engineer for establishing a qualitative degree of pollution severity.

6.2.3 A scale defined in quantitative terms with reference to a test method should be associated with each of the qualitative levels of natural pollution severity for various types of insulators.

6.2.4 Besides being reproducible, a test method should, as far as possible, satisfy the requirement of validity, that is, of a satisfactory simulation of the natural conditions in which the equipment is to be installed. Therefore, the most satisfactory tests, among those presently adopted, may vary from case to case.

6.2.5 It shall be stressed that Table 1 does not cover some environment at situations such as desert areas, where long dry periods are followed by condensation or light rain.

6.2.6 As an example, for line insulators, rather than a specific apparatus, Table 2 gives an indication of the possible requirements corresponding to the various types of tests.

6.2.7 An indication of the required creepage distance is also given, although it is recognized that the performance of surface insulation is greatly affected by insulator shape.

6.2.8 The data in Table 2 are intended to cover the behaviour of equipment at the appropriate voltage, that is, either $U_m/\sqrt{3}$ or U_m in case of a system which may operate with a phase earthed for long durations.

---

*Insulation co-ordination (*second revision*).

TABLE 1 PROVISIONAL SCALE OF NATURAL POLLUTION LEVELS

(*Clauses* 6.2.2 *and* 6.2.5)

POLLUTION LEVEL (1)	ENVIRONMENT (2)	PERFORMANCE OF EXISTING LINES (3)
No significant pollution	Areas without industries and with low density of houses equipped with heating plants; areas with some density of industries or houses but subjected to frequent winds and/or rainfalls. All areas shall be situated far from the sea or at a high altitude, and shall in any case not be exposed to winds from the sea.	No faults are observed in high humidity conditions (fog, mist, etc) on 145 kV lines even when equipped with less than 9 to 10 insulators of the normal type*, nor on 245 kV lines even when equipped with less than 15 such insulators.
Light	Areas with industries not producing particularly polluting smokes and/or with average density of houses equipped with heating plants; areas with high density of houses and/or industries but subjected to frequent clean winds and/or rainfalls; areas exposed to winds from the sea but not too close to the coast (at least about 1 km).	Faults occur in fog conditions on 145 kV lines with less than 9 to 10 insulators of the normal type* and on 245 kV lines equipped with less than 15 such insulators.
Heavy	Areas with high density of industries and suburbs of large cities with high density of heating plants producing pollution; areas close to the sea or in any case exposed to relatively strong winds from the sea.	Faults occur in fog conditions, or when the wind blows from the sea, on HV lines equipped with normal-type insulators* (unless the number of units per string is exceptionally large: more than 11 to 12 units on 145 kV lines and more than 18 units on 245 kV lines).
Very Heavy†	Areas, generally of moderate extension, subjected to industrial smokes producing particularly thick conductive deposits; areas, generally of moderate extension, very close to the coast and exposed to very strong and polluting winds from the sea.	Faults occur in fog conditions or during salt-storms on HV lines, even when equipped with antipollution-type insulators‡ (unless the number of units per string is exceptionally high; more than 11-12 antipollution units on 145 kV lines and more than 18 antipollution units on 245 kV lines).

*Reference is made to normal-type insulators with the following characteristic spacing: 146 mm: diameter: 255 mm, creepage distance: 300 mm.

†Areas of moderate extension very close to highways where a mixture of salt and bitumen may cause severe deposits on the insulators may be subjected to a high pollution level.

‡The reference to antipollution-type insulators is somewhat vague due to the great variety of antipollution-type insulators which are presently in service on HV lines.

TABLE 2 PROVISIONAL RELATION BETWEEN POLLUTION LEVELS, TEST LEVELS AND CREEPAGE DISTANCE

(*Clauses* 6.2.6 *and* 6.2.8)

POLLUTION LEVEL	TYPE OF TEST		RECOMMENDED CREEPAGE DISTANCE/ PHASE-TO-EARTH VOLTAGE
	Salt Fog Method Withstand Salinity	Solid Layer Method Layer Conductivity	
(1)	(2)	(3)	(4)
	kg/m^3	(μs)	(cm/kV rms)
No significant pollution	< 5	5 — 10	2·0 — 2·5
Light	10 — 20	10 — 20	3·0 — 3·5
Heavy	40 — 80	20 — 40	4·0 — 5·0
Very heavy	> 160	> 50	> 6

NOTE 1 — The values reported in the table were established on the basis of normal cap and pin insulators. For other types of insulator and particularly for very large insulators in substations, the correlation with present test methods, between test levels and the creepage distance and service experience is not yet sufficient to give more definite indications.

NOTE 2 — The creepage distances given in the table are those recommended for the various pollution levels and do not necessarily agree with the creepage distances derived from the col 3 of Table 1 which refer to existing lines whose behaviour to power frequency voltage may or may not be satisfactory.

6.2.9 If temporary overvoltages are frequent and severe, it may be necessary to take them into account in prescribing the pollution test.

6.2.10 In the case of stations with a high degree of pollution, when it may be impossible, or extremely expensive, to ask for the necessary performance of equipment under pollution conditions, the alternatives of greasing or washing the insulating surfaces should be considered.

6.3 Ageing — For insulation susceptible to ageing, the problem of specifying suitable test methods are also at present under consideration.

7. CO-ORDINATION BETWEEN STRESSES AND WITHSTAND VOLTAGE FOR RANGE A

7.1 Selection of the Rated Power Frequency Withstand Voltage — Table 1 of IS : 2165-1977* indicates for each system voltage U_m, one value of rated power-frequency withstand voltage only.

---

*Insulation co-ordination (*second revision*).

7.2 Selection of the Rated Lightning-Impulse Withstand Voltage — Table 1 of IS : 2165-1977* leaves open the choice between two corresponding rated lightning-impulse withstand voltages, according to List 1 and List 2. Reduced rated lightning-impulse withstand voltages have been used with good results and for a wide range of equipment over long periods of time. Comprehensive tests have also been performed on different types of equipment for this voltage range to determine their impulse withstand voltages, both for standard lightning impulses and representative switching impluses. It has been found, in particular, that the breakdown voltage of insulation under typical switching impulses is always higher than that of the peak of the power-frequency test voltage. This is one of the reasons why it was not found necessary to introduce a separate switching-impulse withstand in Range A.

The choice between List 1 and List 2 is to be made in accordance with **4.2** of IS : 2165-1977* and the following considerations relevant to the equipment installations:

a) Equipment with no connection to an overhead line,

b) Equipment connected to an overhead line through a transformer, and

c) Equipment connected to an overhead line either directly or through a cable.

7.2.1 Equipment with No Connection to an Overhead Line — A wide variety of installations is covered by this category, for example large underground cable networks in cities, many industrial installations, power stations and ship installations. Equipment in such positions is not subject to any external (lightning) overvoltages but may be subjected to switching overvoltages (*see* **3.4.3.3**).

In **4.2** of IS : 2165-1977*, the conditions are specified under item 1 in which equipment to List 1 may be used in such installations. In all other cases, equipment to List 2 should be used and, with few exceptions, no surge protection is required. One such exception is an electric arc-furnace installation where high overvoltages are liable to develop due to current chopping by a circuit-breaker. Protection by special surge arresters may be required in such a case both between phases and between phases and earth.

7.2.2 Equipment Connected to an Overhead Line Through a Transformer

7.2.2.1 General considerations — Equipment connected to the lower-voltage side of a transformer the higher voltage side of which is supplied from an overhead line is not directly subjected to lightning or

---

*Insulation co-ordination (*second revision*).

switching overvoltages originating on the overhead line. However, due to electrostatic and electromagnetic transference of such overvoltages from the higher-voltage winding to the lower-voltage winding of the transformer, such equipment may be subjected to overvoltages which, in certain circumstances, may exceed its breakdown voltage.

Analytical expressions for the electrostatic and electromagnetic terms of the transferred voltage are given in Appendix A.

For a given transformer the magnitudes and waveshapes of these transferred overvoltages are mainly dependent on the nature of the lower-voltage circuit and, for this reason, it is convenient to consider the selection of the rated lightning-impulse withstand voltage of the equipment and its protection separately for the two basic categories of installation as follows:

Category 1: Equipment connected through transformers to higher-voltage overhead lines, and incorporating connections of moderate length, say up to 100 m, between the lower-voltage side of the transformer and the equipment, such as the main supply switchgear of a cable distribution network or an industrial installation.

Category 2: Generator-transformer installation.

7.2.2.2 *Basic guidance*

a) *Category 1 equipment* — Factors which tend to increase the magnitude of transferred overvoltages for such equipment are:

1) a transformer having a high voltage ratio and high capacitance between windings;
2) a transformer disconnected from its load on the lower-voltage side;
3) low-capacitance connections between a transformer and its associated equipment;
4) a higher-voltage winding which is not earthed (for example delta or unearthed star), or having a star point which is earthed through a high reactance (for example arc-suppression coil);
5) surges having steep wavefronts and surges having long durations; and
6) Switching surges due to energizing a transformer from a remote point on an overhead-line system (that is energizing a transformer feeder).

Estimates of the magnitudes of transferred overvoltages may be made and methods of calculation, with examples, are described in Appendix A.

Category 1 equipment may usually be protected by surge arresters, and where such protection is provided as a normal practice it is not necessary to make these calculations. For other cases, basic guidance is given below on the nature of the transferred voltages, the general influence of circuit conditions and the criteria which may be used to determine whether precautions are necessary.

NOTE 1 — For surge voltages between phases, transferred surge voltages between phases are often higher than those between phase and earth. Compared with the voltage to earth due to a surge on one phase of an overhead line, the phase-to-phase voltage may theoretically approach twice as much for the same surge or three times as much for equal surges of opposite polarity on two phases. Consideration should be given to the probability of this occurring in service and hence the precautions which are necessary to protect against it.

NOTE 2 — For resonant voltages, a condition of resonance between two systems connected by a transformer may cause abnormally large voltages to be transferred through the transformer. It is recommended that an examination of the circuits for possible resonance should be made, and modifications shobld be made as necessary to avoid resonance.

The application of short duration, or steeply rising, voltage surges to the higher-voltage side of the transformer, for example, a lightning stroke to the transmission line very close to the transformer may through capacitive coupling, give a short duration voltage 'spike' on the lower-voltage side. This may exceed the impulse test voltages given in Table 1 of IS : 2165-1977*. On the other hand, the shortest possible front time, determined by wave impedance of the line and transformer input capacitance, is often so long that the capacitively transferred voltage may be ignored.

For Category 1 equipment the most onerous condition rises when the load circuits are disconnected, that is, on the transformer side of the lower-voltage switchgear, since with the load connected its capacitance is usually sufficient to reduce the amplitude of the initial voltage 'spike' to a safe value.

If the capacitance of the connections between the transformer and lower-voltage switchgear is not sufficient to reduce the amplitude of the initial voltage 'spike', either additional capacitance may be connected between the transformer terminals and earth, or equipment in accordance with Table 1, List 2 of IS : 2165-1977* shall be used.

It may also be desirable to consider adding surge arresters. Attention is also drawn to the possibility of increasing inductively transferred overvoltages by additional capacitance. This increase

---

*Insulation co-ordination (*second revision*).

may be reduced by a series damping resistor of carefully adjusted resistance value.

The application of a longer duration voltage surge to the higher-voltage side of the transformer, for example, lightning stroke to the transmission line some distance from the transformer or a switching surge, will, through inductive coupling, give a voltage surge on the lower-voltage side of the transformer having a longer duration and an amplitude which shall be compared with the peak of the power-frequency test voltage given in Table 1 of IS : 2165-1977*. Dangerously high overvoltages can be transferred to the lower-voltage side of a transformer through capacitive coupling from the higher-voltage winding when an earth fault exists on the higher-voltage system and when the neutral of the system is earthed through an arc-suppression coil or when it is isolated.

b) *Category 2 equipment* — Recommendations on the need for surge protection of generator-transformer installations and on suitable types of protective equipment need to be based on consideration of overvoltages of atmospheric origin only since studies have not revealed any more onerous condition likely to arise from transference of switching surges. Corresponding to the front of an incident lightning surge or to the collapse of voltage due to chopping there may be a capacitively transferred voltage of short duration (initial voltage 'spike'). This is independent of the longer-duration voltage which is usually transferred by the combined effect of inductive and capacitive couplings.

The maximum amplitude of the initial voltage 'spike' is highly dependent on details of the design of the installation. Where these are such as to assist capacitive transference there may be justification for making a low-voltage surge-injection test on the installation or on the generator-transformer connected to a circuit simulating the generator and its external connections.

Factors which tend to increase the magnitude of transferred over-voltages for such equipment are :

1) high capacitance between the transformer windings,
2) low-capacitance connections between transformer and generator,
3) high voltage ratio of transformer,
4) a lower-voltage transformer winding not connected to a generator, and
5) surges having steep wavefronts and surges having long duration.

---

*Insulation co-ordination (*second revision*).

If there are indications that the amplitude of the initial voltage spike should be reduced, this may be done effectively by connecting capacitors from each phase to earth by means of low-inductance connections, preferably at the lower-voltage terminals of the transformer. Attention is drawn, however, to the possibility of increasing inductively-transferred overvoltages by additional capacitors.

The longer-duration transference generally takes the form of a unidirectional voltage with superimposed oscillations having a frequency of several kilohertz and if reduction of this is necessary, consideration should be given to the addition of surge arresters.

However, voltage division between the reactances of the generator transformer and the generator normally ensures that the amplitude of the longer-duration transference does not warrant the use of surge arresters. If the generator transformer can be energized from the high-voltage system when the generator is disconnected, this voltage division does not occur and consideration should be given to the higher amplitude of the longer-duration transference affecting that part of the lower-voltage circuit which remains connected to the transformer. For large generator installations, surge arresters located on the generator are not considered as protecting the low voltage side of a connected transformer and calculations should be made. In so far as surge arresters can readily be applied to small installations there is no necessity in these cases for calculations of transference to be made.

The effects of the application of longer duration voltage surges to the higher-voltage side of a transformer and their transference to the lower-voltage side when an earth fault exists on the higher-voltage system when the neutral of that system is earthed through an arc-suppression coil, or if it is isolated, are subject to the same considerations as described for Category 1 equipment.

7.2.2.3 *Selection of insulation level* — The choice of whether to use List 1 or 2 of Table 1 of IS : 2165-1977* and whether additional overvoltage protection is necessary should be based in the first place on service experience with similar installations. It may also be useful to make measurements on an existing similar installation, using a low-voltage impulse-injection method.

For a large installation, and where the necessary data concerning the transformer and the protective equipment are available, it will be useful to calculate the overvoltages liable to be transferred and to compare the results with the appropriate withstand voltages of the equipment to be

---

*Insulation co-ordination (*second revision*).

protected. This is normally advisable only for direct connections between generator and transformer and for low-voltage tertiary windings on large system transformers. If a circuit-breaker is installed between a generator-transformer and its associated generator, consideration should be given to the cases when the breaker is closed and when it is open, although a load is usually connected to the lower-voltage side of the transformer by which transferred voltages may be reduced even in the latter case.

Several methods of calculation have been published and, on the whole, these seem to give similar results. Although no absolute accuracy may be claimed for any method of calculation, comparison between calculation and experimental results on a variety of installations has shown satisfactory agreement. It is therefore deemed appropriate to illustrate a method of calculation by reference to two numerical examples, covering respectively Categories 1 and 2. Examples are given in **A-2**.

7.2.3 *Equipment Connected Directly to an Overhead Line* — Equipment installed in a substation connected directly to an overhead line is subject to direct or indirect lightning overvoltages. Such equipment should, as a general rule, comply with the rated lightning-impulse withstand voltages specified in List 2 (Table 1) of IS : 2165-1977*.

All equipment and, in particular, transformers in such positions require protection by surge arresters or spark gaps. Having regard to the flat impulse-breakdown time characteristic of a transformer winding, transformers should preferably be protected by non-linear resistor-type surge arresters in areas of intense lightning activity. In areas of moderate lightning activity, expulsion-type surge arresters may be used. Where lightning activity is slight, protective spark gaps have proved adequate, particularly where the transformer is connected to a line with earthed crossarms or where the transformer is designed to withstand steep-fronted chopped waves.

The bushings of circuit-breakers, instrument transformers and substation insulators having curved impulse flashover voltage time characteristics, may be effectively protected by existing protective devices on the transformers.

In areas of moderate or low lightning activity, equipment having rated lightning-impulse withstand voltages in accordance with List 1 of Table 1 of IS : 2165-1977* may be used but, in that case, careful attention has to be paid to adequate covervoltage protection. In systems the neutral of which is earthed through a low resistance, surge arresters or spark gaps may be used for this purpose. In systems the neutral of which is earthed through an arc-suppression coil, adequate overvoltage protection shall be provided; if surge arresters are used, those which can withstand repeated operations during the persistence of arcing grounds are recommended.

---

*Insulation co-ordination (*second revision*).

In the absence of any overvoltage-protective device, lightning surges impressed on an overhead line are limited only by sparkovers on the line at the weakest points which the surges meet during their propagation. If not correctly localized, such sparkovers may cause damage to equipment as a result of surge reflections between the point of sparkover and a vulnerable apparatus, such as a transformer winding.

In the case of a substation with a number of lines normally connected to the busbars, the surge voltage arising at the busbars is likely to be sufficiently reduced (*see* **3.5.1**) not to overstress apparatus in the station.

However, such a solution (no overvoltage-protective device) may be acceptable in practice on overhead supply systems in regions of very low lightning activity, at least if equipment to List 2 of Table 1 of IS : 2165-1977*, is used.

7.2.4 *Equipment Connected to an Overhead Line Through a Cable* — Insulation co-ordination in this case is not only concerned with the protection of the substation equipment but also with that of the cable. In this respect the two ends of the cable may be assumed to be subjected approximately to the same overvoltage amplitudes.

When a lightning surge propagated along an overhead line impinges on a cable, the latter acts, substantially, like a capacitance. Thus the front steepness of the original surge is reduced as the surge voltage enters the cable. The amplitude of U_2 of the surge entering the cable is given by:

$$U_2 = \frac{2Z_2}{Z_1 + Z_2} U_1$$

where

U_1 = amplitude of surge voltage on overhead line;

Z_1 = surge impedance of overhead line, in practice $Z_1 = 400$ to 500 ohms; and

Z_2 = surge impedance of cable; in practice $Z_2 = 25$ to 50 ohms but for some types of cable it may be as low as 5 ohms.

This initial surge is reflected at the station end of the cable in accordance with the effective surge impedance at the station busbar. Subsequent reflections along the cable continue to be governed by the above equation with due regard to the fact that U_1 and Z_1 invariably refer to the wave which impinges on a point of reflection while U_2 and Z_2 refer to the reflected wave.

---

*Insulation co-ordination (*second revision*).

Provided at least one further cable of a few hundred metres length is permanently connected to the busbar, the surge voltage to which the cable and the station equipment are subjected is notably lower than that on the line on which the surge originated and this reduction is all the greater, the lower the surge impedance of the cable.

However, if the cable only supplies a terminal transformer the incident wave is doubled in amplitude at the transformer. As a result of successive reflections at both cable terminations, this voltage build-up increases towards twice the amplitude until no further energy is supplied by the original surge.

For a station to which at least two cables are connected, a decision on the adequacy of equipment to List 1 of Table 1 of IS : 2165-1977* or the need for overvoltage protection may be determined from the above equation.

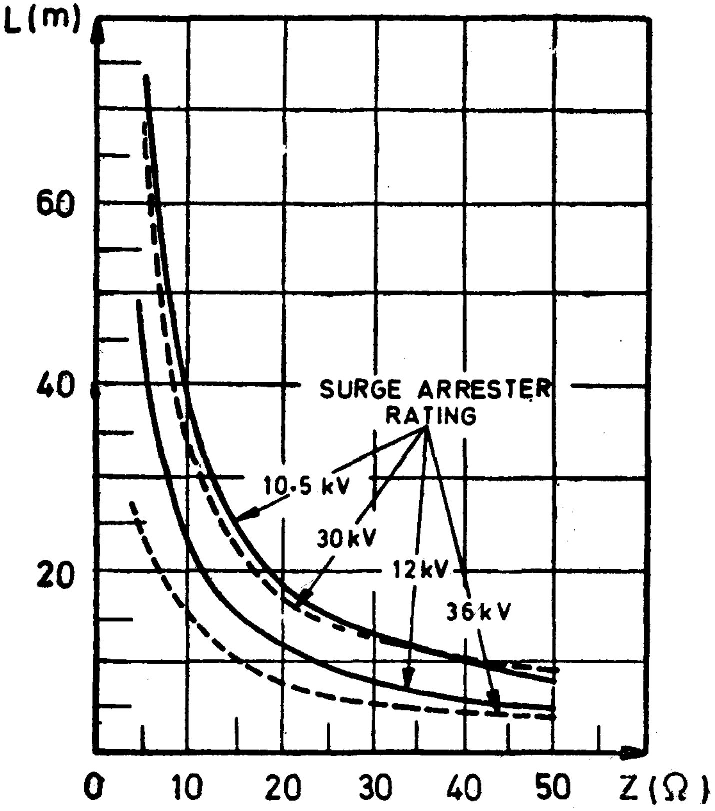
However, in the case of a terminal station, the ultimate surge-voltage amplitudes developed at the cable terminations as a result of successive reflections are a function of the amplitude and duration of the original lightning-surge voltage on the line, the length of the cable, and if the stroke is fairly close to the cable, also the reflections from the point of strike. For lines with fully insulated crossarms, the resulting voltage amplitudes are so high that, even using substation equipment and a cable with lightning-impulse withstand voltages to List 2 of Table 1 of IS : 2165-1977*, surge arresters shall be used at the line/cable junction. As an example, the maximum cable lengths are plotted in Fig. 3 for which the cable and the substation equipment may be protected by surge arresters at the line/cable junction only; the figure demonstrates the considerable benefit of the use of a cable of low surge impedance. The protection is fully effective against direct and indirect lightning surges and surges due to back flashover provided these originate a few spans away from the line/cable terminations. If the cable length exceeds the values indicated in Fig. 3 additional surge arresters are required at the substation end of the cable. If surge arresters with lower sparkover voltages than specified in IS : 3070 (Part I)-1974† are used the cable lengths indicated in Fig. 3 may be increased in proportion to the differences indicated by comparing say a 10·5 kV with a 12 kV surge arrester.

For lines with earthed crossarms feeding a cable with terminal transformer the impulse flashover voltage to earth of the line insulation is only slightly higher than the corresponding value in List 2 of Table 1 of IS : 2165-1977*. In such a case, surge arresters may be required at the line/cable junction and it may also be necessary to use these at the station end of the cable.

---

*Insulation co-ordination (*second revision*).

†Lightning arresters for alternating current systems: Part I Non-linear resistor types lightning arresters.



Z = cable surge impedance in ohms
L = cable length in metres

FIG. 3 MAXIMUM PERMISSIBLE CABLE LENGTH WITH SURGE ARRESTER OF LINE/CABLE JUNCTION ONLY

The foregoing considerations apply to direct strokes a few spans away from the cable termination. Full protection against very close strokes is generally not possible.

In areas of moderate or low lightning activity, protective spark gaps may be used in place of surge arresters. However, if the spark gaps at the line/cable junction are earthed through a low resistance (the usual case) and if the cable is terminated in a transformer, dangerous surge voltages can be developed across the transformer winding. The spark gaps at the line/cable junction should therefore be earthed through a resistance of several tens of ohms, ideally equalling the surge impedance of the cable. Greatly improved protection may be achieved by installing additional spark gaps across the line insulators on the first and second poles in front of the line/cable termination and, in this case, the earthing resistances of these additional spark gaps are immaterial.

8. CO-ORDINATION BETWEEN STRESSES AND WITHSTAND VOLTAGE FOR RANGE B

8.1 Selection of the Rated Power Frequency Withstand Voltage and the Rated Lightning Impulse Withstand Voltage

8.1.1 Many considerations concerning voltages in Range A still apply to Range B. However, the variety of equipment and situations is not so great as in Range A.

8.1.2 In Table 2 of IS : 2165-1977*, one value of rated lightning-impulse withstand voltage only is associated with each value of rated power-frequency withstand voltage. Therefore, there will be a unique choice for the rated power-frequency withstand voltage and the rated lightning-impulse withstand voltage.

8.1.3 With each value of U_m are associated one to three values of rated power-frequency withstand voltage with a corresponding rated lightning-impulse withstand voltage.

8.1.4 The choice between the possible alternatives for U_m above 72·5 kV shall take account of:

a) the neutral earthing conditions; and
b) the existence of protective devices, their characteristics and their distance from the equipment considered.

8.1.5 The conventional safety factors normally employed in the application of surge arresters in Range B are given in **5.5.1**.

9. CO-ORDINATION BETWEEN STRESSES AND WITHSTAND VOLTAGE FOR RANGE C

9.1 Insulation Design to Power-Frequency Voltage and Temporary Overvoltages — For this range of voltage, power-frequency tests are to be specified in the relevant equipment specifications, in accordance with the considerations in **6**, and taking into account that the temporary phase-to-earth overvoltages will not usually exceed 1·5 p.u. (per unit) for one second on each occasion.

---

*Insulation co-ordination (*second revision*).

9.2 Insulation Design to Switching and Lightning Overvoltages — IS : 2165-1977* proposes two methods for coordination of insulation in respect of switching and lightning overvoltages, namely, a conventional and a statistical method.

9.2.1 *Conventional Method* — This is based upon the established concepts of maximum overvoltages stressing insulation and of minimum strength of the insulation (**2.20** and **2.23** of IS : 2165-1977*).

The statement of the minimum strength and that of the maximum overvoltages are rather arbitrary since a rigorous rule may seldom be followed in the evaluation of the upper and lower limits of the insulation strength and overvoltage value, which are intrinsically random variables.

Insulation is selected in such a way as to achieve a sufficient margin between the maximum overvoltage and the minimum strength. This margin is intended to cover the uncertainties of the designer in the evaluation of the maximum overvoltage and of the minimum strength, and no endeavour is made to assess quantitatively the risk that insulation may break down.

The conventional safety factors normally employed in the application of surge arresters in Range C are to be found in **5.5.1**.

9.2.2 *Statistical Method* — This attempts to quantify the risk of failure for use as a safety index in insulation design.

Rational insulation design of a transmission system should be based on the minimum of the installation cost plus the capitalized yearly operational cost and yearly cost of failure, the latter being calculated as the estimated cost of failure of insulation multiplied by the average expected number of insulation failures per year.

In order to evaluate the average expected number of failures per year of a piece of insulation located at a given point of the system in consequence of overvoltages, all the events giving rise to overvoltages which may affect insulation design should be taken into consideration. Then for each type of event considered the frequency of occurrence during the year and a separate distribution of the overvoltage amplitude would be required.

NOTE — It is evident that the amplitudes of all the overvoltages occurring in a system can not be combined in one distribution but that only overvoltages identified by the same location and cause may be considered as statistically homogeneous. Actually, since the overvoltage severity differs for waveshapes which are comparable respectively with a lightning impulse and with a switching impulse (*see* Note under **2.17** and **2.18** of IS : 2165-1977*) the overvoltage amplitude could be said to be homogeneous only if identified by the same location, cause and shape. However the overvoltages due to the same cause at a given location have broadly a similar shape

---

*Insulation co-ordination (*second revision*).

and, therefore, those identified by the same cause and location may, for the sake of simplicity, be regarded as homogeneous. If problems of standardization of the equipment of an entire network are to be dealt with, an extension of the concept of a homogeneous group of overvoltages needs to be considered. In this case a group of overvoltages may be said to be homogeneous if the overvoltages occur in similar locations of the system due to the same cause. For example the reclosing overvoltages on the bus-bars (sending-end) of any substation of the system may be considered as a homogeneous group of overvoltages.

However, a process of insulation design and coordination as outlined above involves too many difficulties. The statistical approach considered here is therefore restricted to checking that the risk of insulation failure due to any foreseeable type of event causing overvoltages in the system is within acceptable limits. These limits depend on the frequency of occurrence of the type of event and on the consequences of the failure of the piece of insulation under consideration.

Fortunately, the types of event which are significant in insulation design are generally a few in number to allow an analytical approach. For instance, the insulation withstand to switching surges of many pieces of equipment in a system is, in general, determined primarily by reclosing overvoltages.

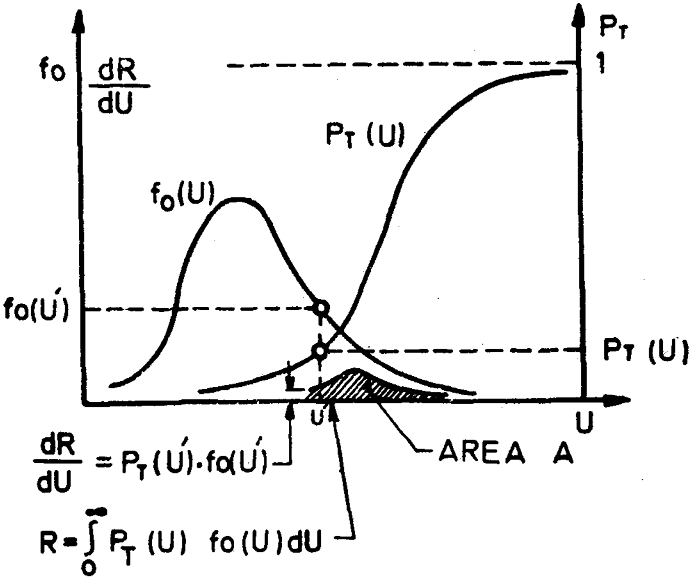
If the frequency distribution of overvoltages caused by a given type of event and the corresponding insulation strength are known, the risk of failure may be expressed numerically, as will be shown below.

Let the withstand strength of a given piece of insulation within a given time interval Δ_T be defined by the probability $P_{\mathrm{T}}(U)$ of discharge of the insulation when it is subjected to an overvoltage of value U (*see* Fig. 4). Furthermore let the distribution of the overvoltages stressing the same piece of insulation for the specific type of event considered be defined by the probability density $f_0(U)$. Then the probability that an overvoltage of value comprised between U' and $U' + dU$ may occur is $f_0(U')\, dU$. The probability density of failure of the insulation due to an overvoltage of value U' is, therefore, the product of the probability density that an overvoltage of value U' may occur and the probability that the insulation may fail under an overvoltage of value U' that is:

$$\frac{\mathrm{d}R}{\mathrm{d}U} = f_0 (U') \,.\, P_{\mathrm{T}} (U') \qquad \ldots (6)$$

The probability of failure for a value of U at random, that is the risk of failure R for an event of the type considered, will then be:

$$R = \int_0^{\infty} f_0 (U).P_{\mathrm{T}} (U).\mathrm{d}U \qquad \ldots (7)$$



R = shaded area

FIG. 4 EVALUATION OF THE RISK OF FAILURE OF A PIECE OF INSULATION

This expression shows the general principle of the method by which the probability of failure may be assessed. It assumes that $f_0(U)$ and $P_T(U)$ are uncorrelated.

NOTE — In principle formula (7) applies to a single-phase piece of insulation only. If several pieces of equipment, connected in parallel on the same phase, are subjected to the same overvoltage then it may be assumed that the overall risk is equal to that of a single piece of equipment multiplied by the number of pieces in parallel. This is valid if we take into consideration the fact that the risk of failure acceptable for substation insulation is usually very low.

Sometimes it is necessary to evaluate the risk of failure of at least one phase of a three-phase section of the system following a switching operation (for example a closing operation). This risk may be obtained by multiplying by 3 the risk evaluated according to formula (7) if the probability density $f_0(U)$ of the overvoltages may be assumed to be equal on all three phases.

An alternative method is to establish the overvoltage probability density $f_0(U)$ by considering only the highest value of the overvoltages caused on the three phases by a switching operation. Then the risk of failure is evaluated by making use of formula (7).

The former approach gives risk values higher than the actual ones; the latter lower. Obviously the two approaches give results differing by less than 1 to 3.

The mathematical model chosen for defining the severity of an overvoltage in formula (7) is based upon a few simplifications. In fact the following assumptions are made:

a) Peaks other than the highest one in the wave-shape of overvoltages are disregarded.

b) The wave-shape of the highest peak is assumed to be equal to that of the standard switching or lightning impulse.

c) The highest overvoltage peaks are assumed to be all of the same polarity; to be on the safe side the more severe polarity will be used.

As regards switching overvoltages, which are the overvoltages of predominant importance in insulation design of EHV systems, assumption (a) is such as to give a calculated risk of failure lower than the actual risk. Assumptions (b) and (c) result in a calculated risk higher than the actual one, since the standard wave-shapes are so chosen as to establish the lowest withstand of apparatus (*see* **7.2** of IS : 2165-1977*).

In general, considering the opposite effects of the assumptions made, the risk of failure calculated by means of formula (7) gives risk values greater by about 0·5 to 1 decades (5 to 10 times) than the actual values. Normally formula (7) is, therefore, conservative. As said above, formula (7) may be applied for all the specific types of events significant in insulation design.

Furthermore, it is clear that the accuracy in the calculation of the risk failure greatly depends on the accuracy in the determination of the overvoltages and of the impulse discharge probability of insulation. Since accuracy of these is seldom satisfactory, the accuracy of the calculated risk of failure can be correspondingly poor.

However, the risk of failure has a precise physical meaning (contrary to the conventional safety factor). By making use of statistical methods it is therefore, possible to coordinate the security levels of the various parts of system according to the consequences of a fault. Furthermore, it is possible to carry out sensitivity analysis (for example, the effect of a change in the overvoltage severity or insulation withstand capability on the probability of faults). Statistical methods do, therefore, enable the engineer to take a decision on a rational basis.

According to the statistical method, insulation is selected in such a way as to obtain a calculated probability of failure lower than, or equal

---

*Insulation co-ordination (*second revision*).

to, a predetermined value that characterizes the required safety level. Referring to Fig. 4 a change in the insulation level shifts the curve representing the discharge probability of the insulation $P_T(U)$ along the U axis with a consequent modification of the shaded area A which represents the probability of failure R for U at random.

The statistical approach may require successive series of tentative designs and evaluations of risk, until a design that satisfies the risk prerequisites is found.

Formula (7) may also be applied to determine the probability of failure of an insulation protected by spark gaps or surge arresters, if $P_T(U)$ is taken as the discharge probability of the insulation in presence of the protective device. If the time-to-discharge of the protective device can be considered always shorter than that of the insulation to be protected an equally valid and simpler method is to use formula (7) and to take $f_0(U)$ as the overvoltage probability density modified by the protective device (*see* Appendix C).

The use of digital computers makes it easy to evaluate the risk of failure, and therefore the insulation design, once the overvoltage distribution and the discharge probability curves of insulation are known.

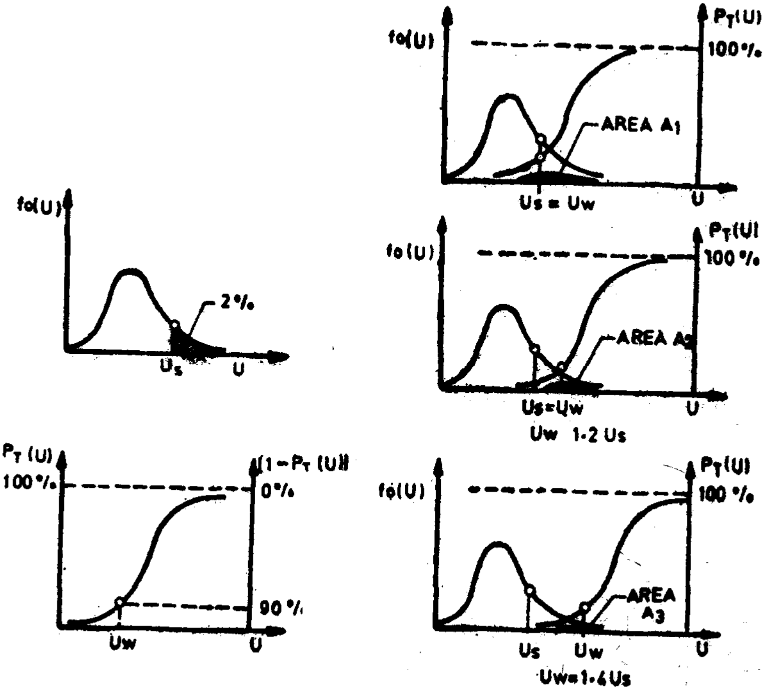
9.2.3 *Simplified Statistical Method* — Sensitivity analyses and ready evaluations of the risk of failure may be made on the basis of simplified statistical methods in which the calculations are performed once and for all by making some generally acceptable assumptions concerning the mathematical laws by which the actual distributions of the overvoltages and of the discharge probability of insulation are represented for example by assuming them to be Gaussian with known standard deviations.

With these assumptions the complete distribution of overvoltage and the discharge probability of insulation may be defined by one point only corresponding to a given reference probability and called in IS : 2165-1977* 'statistical overvoltage' (*see* **2.19**) and 'statistical impulse withstand voltage' (*see* **2.22**) respectively. The risk of failure may be correlated with the margin between these two values, so that the approach becomes rather similar to that in the conventional method.

Figure 5 gives a graphical explanation of the method. Figure 5A shows frequency distributions of overvoltage and insulation strength, where the statistical overvoltage is indicated by U_s and the statistical withstand voltage by U_w. In Fig. 5B, the overvoltage distribution and the electric strength distribution are superimposed for three values 1·0, 1·2 and 1·4 of the statistical safety factor (γ) relating U_s and U_w. The correlation between statistical safety factor and risk of failure is given in Fig. 5C.

---

*Insulation co-ordination (*second revision*).

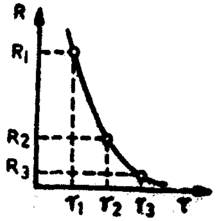


5A U_s = statistical overvoltage *R* placed on the probability density curve [the shaded area (2%) represents the reference probability].

U_w = statistical withstand voltage placed on the discharge probability curve (90% represents the reference probability).

5B Three attempts at determining the risk of failure (area *A*) for statistical safety factors.

$$\frac{U_w}{U_s} = \gamma = 1\cdot 0,\ 1\cdot 2 \text{ and } 1\cdot 4$$



5C Relation between the statistical safety factor (γ) and the risk of failure '*R*' (measured by area *A*).

FIG. 5 SIMPLIFIED STATISTICAL METHOD

The reference probability of the overvoltages is chosen in this standard equal to 2 percent. The reasons of this choice are discussed later in this clause. As regards the reference probability of the withstand voltage the 90 percent value was chosen in IS : 2165-1977* for the reasons given in **4.3** of this standard.

As regards switching surges, Fig. 6, 7 and 8 illustrate the relationship between risk of failure and the statistical safety margin for air insulation in different cases.

The discharge probability curve of insulation was assumed to be Gaussian as stated in **4.3** with k (formula 5 in **4.3**) equal to 1 and σ_T (formula 2 in **4.3**) equal to 6 percent, 8 percent and 10 percent (*see* Fig. 6, 7 and 8 respectively). If k were to be taken as differing from 1, the statistical safety factor given for $k = 1$ would have to be multiplied by $\frac{1}{k}$.

Figure 6 is applicable to laboratory conditions, while Fig. 7 is generally applicable to service conditions. Figure 8 may be used for particularly severe conditions (high values of σ_a in formula 2). In all the three cases the overvoltage distributions were assumed to be Gaussian truncated at three and four times the standard deviation σ_s, or not truncated and with standard deviation σ_s equal to 10 percent, 15 percent and 20 percent. Figures 6 to 8 give the average correlation between statistical safety factor and risk of failure as well as the upper and lower envelopes of the correlations obtained when considering the nine overvoltage distributions resulting from all the possible combinations of values of standard deviation and upper truncation point.

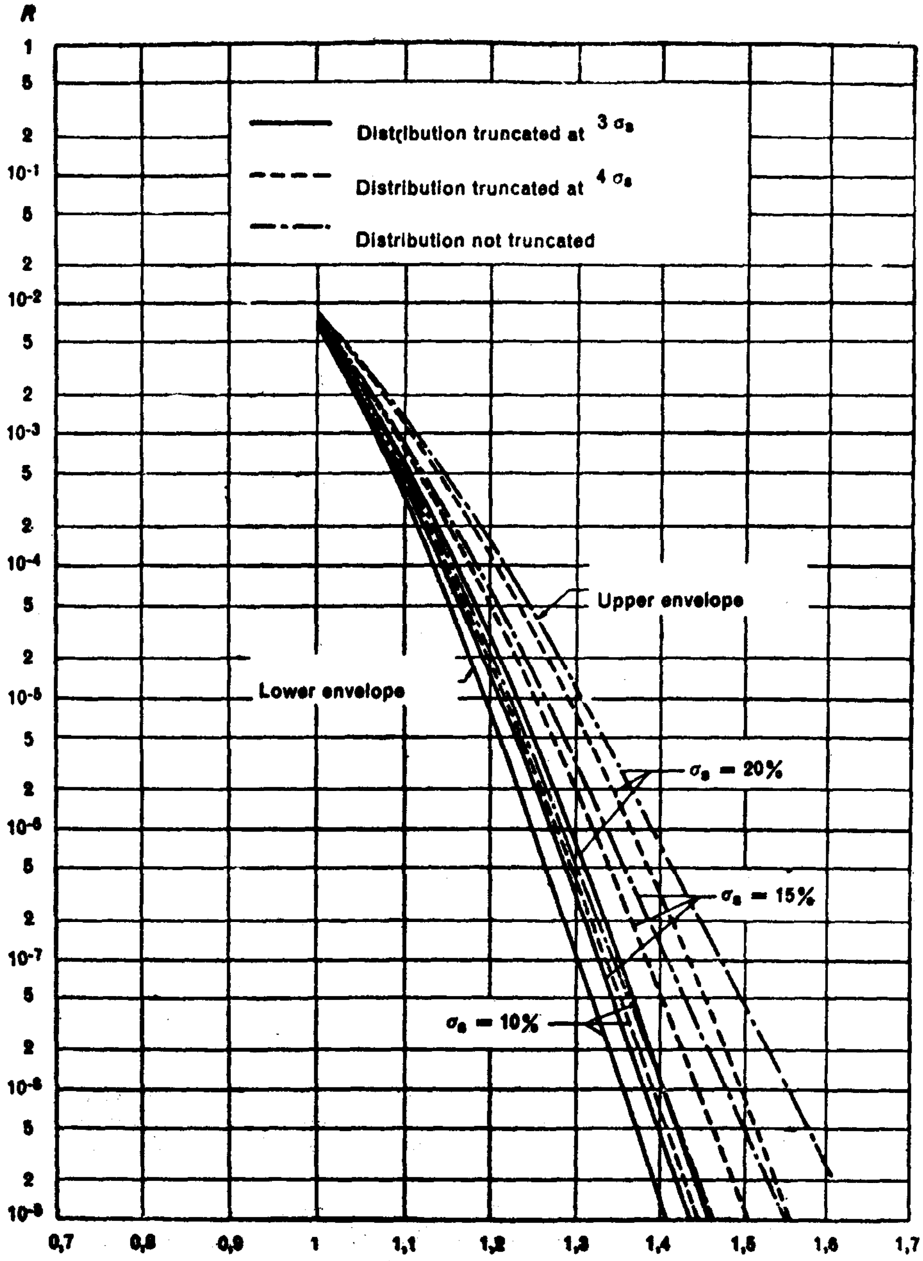
The choice of a Gaussian distribution to define the overvoltage severity does not mean that other distributions (for example extreme value distribution) may not give better approximations, but that Gaussian distributions match actual distributions reasonably well over the range of interest.

The correlation between the statistical safety factor and risk of failure appears to be only slightly affected by changes in the shape of the overvoltage distribution. This is due to the fact that the 2 percent value chosen as a reference probability of the overvoltages falls in that part of the overvoltage distribution which gives the major contribution to the risk of failure in the range of risk considered. If, on the contrary, a much lower or higher value were chosen, the influence of the shape of the overvoltage distribution would have been very pronounced.

Figures 6 to 8 give the risk of failure of a piece of single-phase equipment (for example a post insulator). If the risk of failure of several pieces of equipment is required reference may be made to the Note under **9.2.2**.

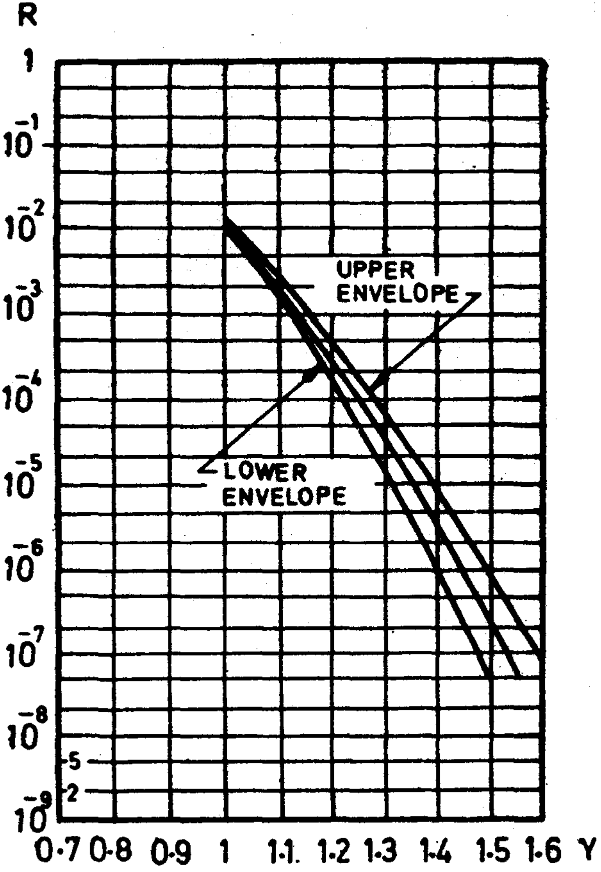
---

*Insulation co-ordination (*second revision*).



Standard deviation of overvoltage distribution σ_s = 10, 15 and 20 percent
Standard deviation of insulation σ_T = 6 percent

FIG. 6 CORRELATIONS BETWEEN RISK OF FAILURE (R) AND STATISTICAL SAFETY FACTOR (γ) FOR VARIOUS SWITCHING SURGE DISTRIBUTIONS

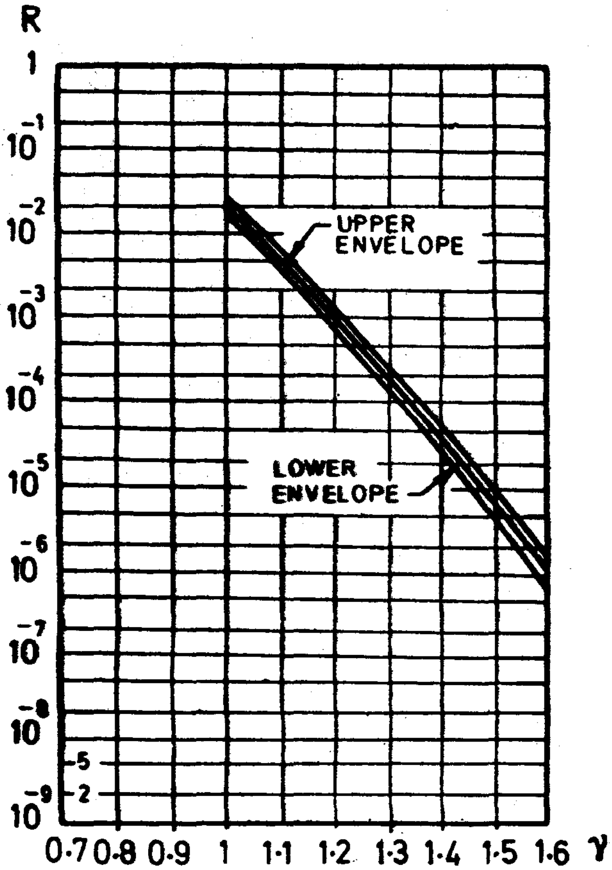


Standard deviation of insulation $\sigma_T = 8$ percent

FIG. 7 CORRELATIONS BETWEEN RISK OF FAILURE (*R*) AND STATISTICAL SAFETY FACTOR (γ) FOR VARIOUS SWITCHING SURGE DISTRIBUTIONS

For example, if the number of single-phase pieces of equipment at a line entrance is equal to 21 (seven on each phase) and the risk of failure of each for a three-phase reclosing is 10^{-4}, then the risk of failure for the whole line entrance will be close to $2 \cdot 1.10^{-3}$.

Extension of this method to overhead lines is possible but presents problems particularly for long lines with which the present guide does not attempt to deal.



Standard deviation of insulation σ_T = 10 percent

FIG. 8 CORRELATIONS BETWEEN RISK OF FAILURE (*R*) AND STATISTICAL SAFETY FACTOR (γ) FOR VARIOUS SWITCHING SURGE DISTRIBUTIONS

As regards lightning surges, analogous correlations between statistical safety factor and risk of failure are given in Fig. 9 to 11 for comparison purposes always for air insulation.

Assumptions similar to those of the previous paragraphs were made as regards the discharge probability curve of insulation to lightning surges.

The lightning overvoltage distributions were assumed to be Gaussian and not truncated, with standard deviations equal to 40 percent and 60 percent. It is thought that such distributions approximate actual lightning overvoltage distributions quite well around the 2 percent value.

Figures 9, 10 and 11 give the correlation between statistical safety factor and risk of failure for both overvoltage distributions and for standard deviations of insulation equal to 3 percent, 5 percent and 7 percent respectively.

NOTE — The correlations between statistical safety factor and risk of failure given above apply to self-restoring insulation only. However, they may be considered acceptable for the entire equipment in most cases for the following reasons:

The tests described in **7.4** and **7.5** of IS : 2165-1977* are intended to ascertain the impulse insulating ability of self-restoring equipment and combined equipment respectively. Such tests do not allow any discharge on the non-self-restoring parts of the apparatus. Consequently, when both the self-restoring pieces of insulation of the same apparatus are designed on the basis of the same risk of failing the test, the non-self-restoring parts will have an inherently lower discharge probability than the self-restoring parts in respect of overvoltages of the same amplitudes as those of the impulses applied during the test.

Consequently, it may be stated that risk failure of the non-self-restoring parts of self-restoring equipment (tested according to **7.4** of IS : 2165-1977*) is lower than that of the self-restoring parts if the major contribution to the overall risk of failure is given by overvoltages in the range of $U_{50\%} \pm 2\sigma$.

For combined insulation equipment the non-self-restoring parts will be designed for a low risk of failure at test voltage. In the cases where the major contribution to the failure risk (calculated on the basis of the statistical withstand voltage) is given by overvoltages around the test voltage the evaluation of the risk of failure may be carried out as for self-restoring insulation.

The foregoing considerations naturally presuppose that wave-chopping by a self-restoring piece of insulation does not cause serious stresses in the non-self-restoring insulation of equipment and does not cause ageing of insulation.

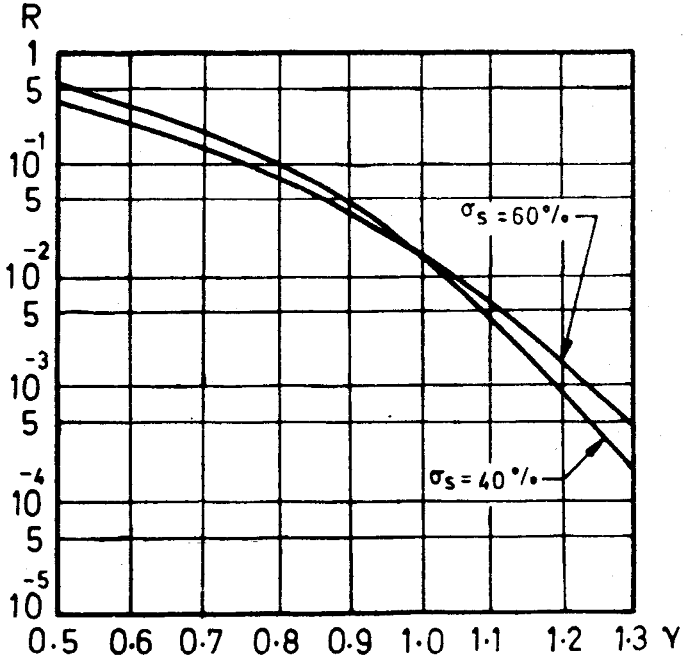
9.3 Block Diagram of the Insulation Design and Co-ordination of an Electric Installation — Most predictions or analyses of system overvoltage levels assume that a piece of equipment (for example, a circuit breaker) will operate as designed. In other cases, an arbitrary limit may be placed on the 'credible' severity of surges, as is often done in the case of lightning. It is obvious that surge levels based on such assumptions will sometimes be exceeded.

Whether or not it is necessary to take this into account, depends largely on the consequence of failure resulting from such abnormally high overvoltages. For example, the consequences of transformer or reactor failure are so serious that there insulation co-ordination must usually provide for even extreme contingencies. This is achieved by applying surge arresters at their terminals. There are other types of equipment such as post insulators, disconnecting switches, etc, where the consequence of failure is not so serious as to warrant application of surge arresters.

In developing a sequence of insulation design and co-ordination of an electrical system in the form of a block diagram, it is convenient to

---

*Insulation co-ordination (*second revision*).



Standard deviation of insulation σ_T = 3 percent
Standard deviation of overvoltage distribution σ_s = 40 and 60 percent

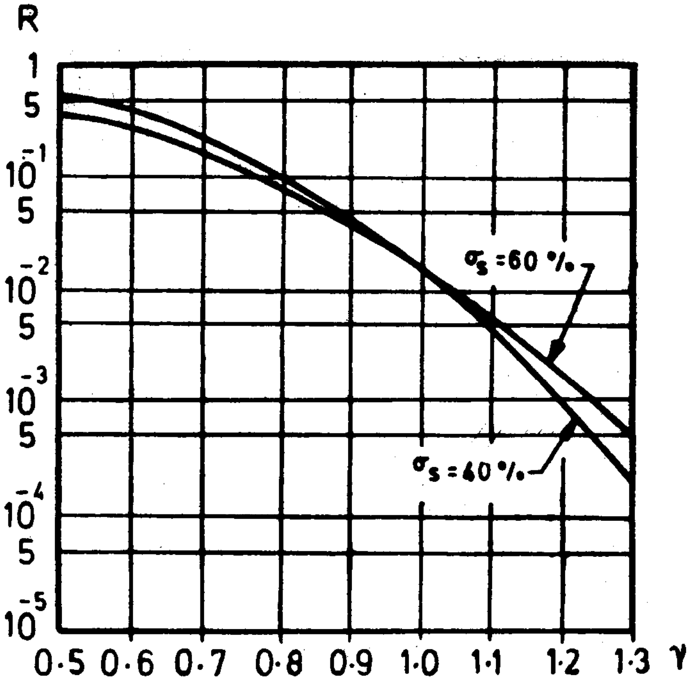
FIG. 9 CORRELATIONS BETWEEN RISK OF FAILURE (*R*) AND STATISTICAL SAFETY FACTOR (γ) FOR VARIOUS LIGHTNING SURGE DISTRIBUTIONS

differentiate between a Case I (surge arrester protection) and Case II (no surge arrester or remote surge arrester protection). A block diagram illustrating the method to be adopted is shown in Fig. 12.

The first step in insulation co-ordination (Block 5), common to all types of equipment, has the purpose of ensuring the equipment ability of withstanding power-frequency voltage under normal conditions and under temporary overvoltages.

The system engineer will specify an equivalent pollution severity test level for insulation susceptible to contamination, however, no special specifications will be given for insulation susceptible to ageing (*see* **9.1**).

If the expected phase-to-earth temporary overvoltages (Block 3) are more severe than the overvoltages taken into consideration in the relevant equipment specification in specifying the power-frequency tests discussed



Standard deviation of insulation σ_T = 5 percent
Standard deviation of overvoltage distribution σ_s = 40 and 60 percent

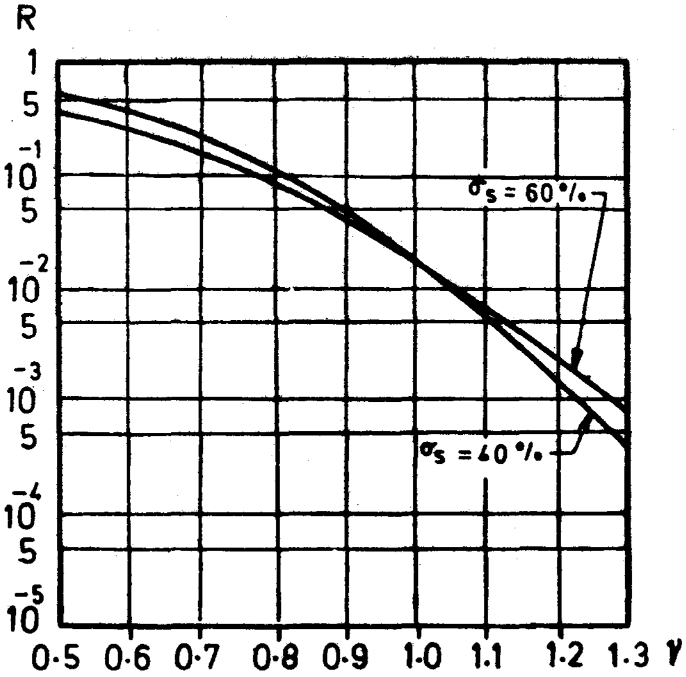
FIG. 10 CORRELATIONS BETWEEN RISK OF FAILURE (*R*) AND STATISTICAL SAFETY FACTOR (γ) FOR VARIOUS LIGHTNING SURGE DISTRIBUTIONS

in **3.6** of IS : 2165-1977*, it will be necessary to specify different voltage levels or durations of the test or to adopt suitable means or operational procedures to reduce temporary overvoltages in the system (feedback from Block 5 to Block 2 dashed line).

Insulation design as regards operating voltages and temporary overvoltages leads to a certain withstand of the equipment to both switching and lightning impulses. For instance, if a given withstand salinity is required for a post insulator, a minimum distance in air is obtained which varies according to the post insulator type (*see* Appendix E). The equipment will, therefore, exhibit a certain withstand to switching surges due to requirements imposed by the operating voltages and temporary overvoltages. These influences are indicated in Fig. 12 by dotted lines (for example, from Block 5 to Block 7 and Block 8).

---

*Insulation co-ordination (*second revision*).



Standard deviation of insulation σ_T = 7 percent

Standard deviation of overvoltage distribution σ_S = 40 and 60 percent

FIG. 11 CORRELATIONS BETWEEN RISK OF FAILURE (*R*) AND STATISTICAL SAFETY FACTOR (γ) FOR VARIOUS LIGHTNING SURGE DISTRIBUTIONS

Then it is necessary to consider Case I and Case II separately. Examples of selection of the rated switching and lightning impulse withstand voltage are given in Appendix D.

As regards apparatus of the first type (Case I), choice of the rated switching and lightning impulse withstand voltages is usually made as follows:

a) Choose the rated voltage of the surge arresters on the basis of the temporary overvoltages (Block 6); thus the protective levels of the arresters under switching and lightning impulses will also be determined at least within certain limits.

b) Choose the rated switching and lightning impulse withstand voltages of the apparatus on the basis of conventional safety factors dictated by experience (*see* **5.4.1** and **5.5.1**).

c) Adopt suitable means in system design or suggest suitable operating procedures to reduce temporary overvoltage if an economic incentive exists to reduce insulation levels (start again from Block 2).

This procedure of selecting the rated switching and lightning impulse withstand voltage of the apparatus disregards the severity of the actual switching and lightning overvoltages by which the apparatus connected in parallel with the surge arresters may be stressed since it is based on the protective level of the surge arresters only.

The insulation levels of the apparatus of Case II are usually chosen according to the following steps:

a) Choose the rated switching-impulse withstand voltage of the apparatus on the basis of an acceptable risk which may be estimated directly on the basis of the expected distributions of the overvoltages and of the discharge voltages (statistical method), or by means of the correlations given in **9.2.3** between the risk of failure and the statistical safety factor (simplified statistical method). Actually these correlations apply to self-restoring insulation only, but normally they may be considered acceptable for the entire equipment (*see* Note under **9.2.3**).

NOTE — Protection against switching surges afforded by surge arresters installed close to equipment in Case I and gaps installed at the line-entrance may often be discounted as regards Case II apparatus for the following reasons:

i) Most of the types of equipment belonging to Case II (especially the line-entrance apparatus) may at times be isolated from the surge arresters installed in the station to protect Case I apparatus;

ii) With the present technology of surge arresters, the protective level against switching impulses is often greater than, or equal to the highest switching overvoltage which may occur with correct behaviour of system apparatus. Insulation must therefore be designed to withstand these overvoltages; and

iii) Spark gaps may not provide a substantial degree of protection against switching surges if undesired sparkovers are to be avoided. This point is discussed in Appendix C.

In Fig. 12 the block between Block 4 and Block 8 is therefore indicated by dashed lines.

b) Adopt suitable means in system design to reduce switching overvoltages, if this is possible and if an economic incentive exists in reducing the rated switching impulse withstand voltage of apparatus. No economic incentive may exist in reducing insulation : for instance if the withstand to normal operating voltages and temporary overvoltages calls for ‘ higher insulation ’ than switching surges (dotted line between Block 5 and Block 8).

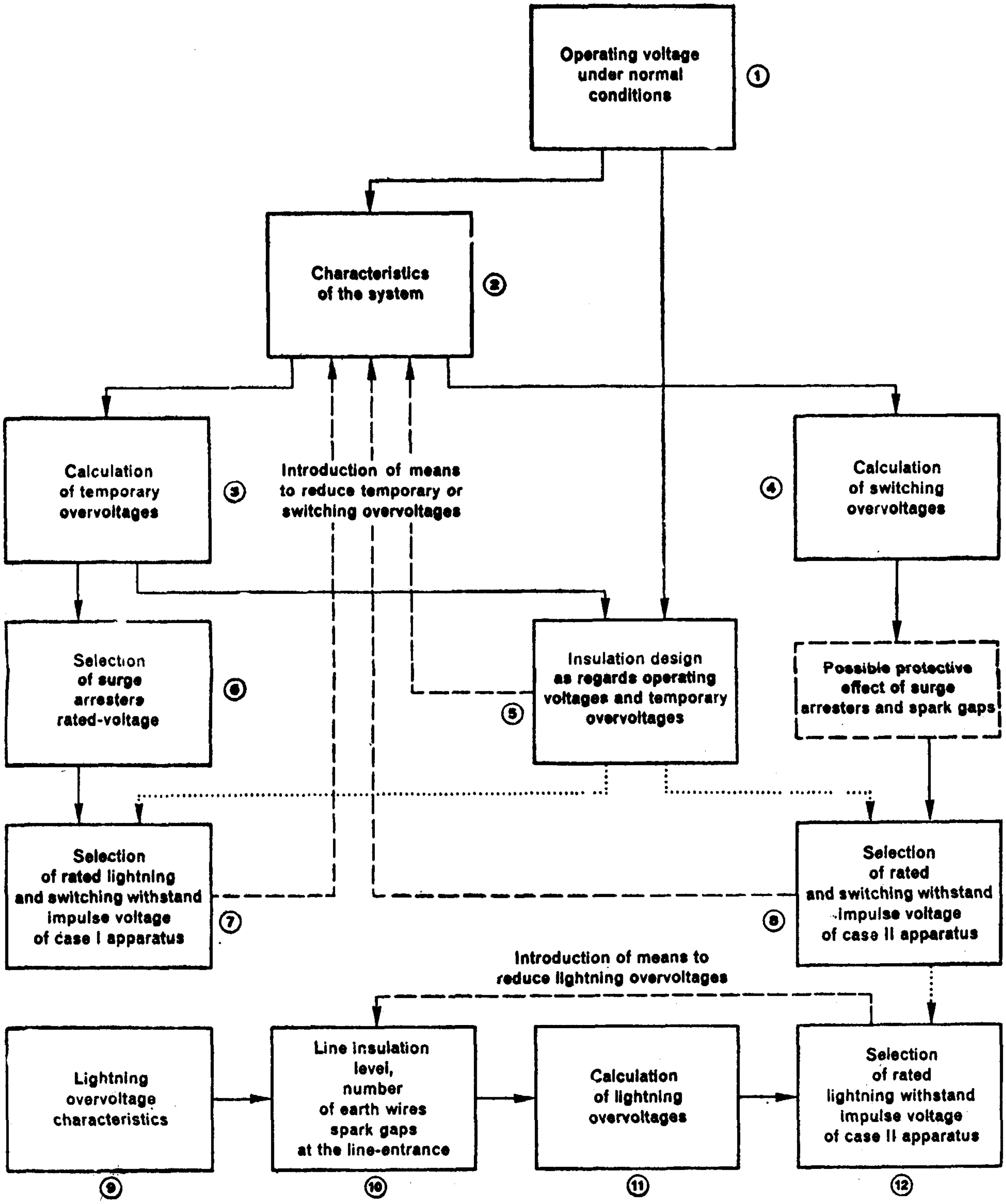

Operating voltage under normal conditions
①
Characteristics of the system
②
Calculation of temporary overvoltages
③
Introduction of means to reduce temporary or switching overvoltages
④
Calculation of switching overvoltages
Selection of surge arresters rated-voltage
⑥
Insulation design as regards operating voltages and temporary overvoltages
⑤
Possible protective effect of surge arresters and spark gaps
Selection of rated lightning and switching withstand impulse voltage of case I apparatus
⑦
Selection of rated and switching withstand impulse voltage of case II apparatus
⑧
Introduction of means to reduce lightning overvoltages
Lightning overvoltage characteristics
⑨
Line insulation level, number of earth wires spark gaps at the line-entrance
⑩
Calculation of lightning overvoltages
⑪
Selection of rated lightning withstand impulse voltage of case II apparatus
⑫

Fig. 12 Block-Diagram of Insulation Co-ordination and Design

As in the Original Standard, this Page is Intentionally Left Blank

c) Verify that the rated lightning impulse withstand voltage, corresponding (in Table 3 of IS : 2165-1977*) to the rated switching impulse withstand voltage determined above [Items (a) and (b)], guarantees a satisfactory performance of the apparatus under lightning overvoltages. This should be done on the basis of the expected distribution of the lightning overvoltages and of the discharge voltages or by means of the correlation given in **9.2.3** but for the sake of simplicity it is often done on a conventional basis (*see* Appendix D).

Consider that only the highest value of rated lightning impulse withstand voltage of each line should be used for apparatus not effectively protected by a surge arrester (*see* **6.4** of IS : 2165-1977*).

d) Provide means to reduce the amplitude of lightning surges† (feedback from Block 12 to 10) or choose a rated lightning impulse withstand voltage higher than the one determined on the basis of Table 3 of IS : 2165-1977* if too high a risk of failure to lightning overvoltages results from Item (3). In the latter case the value of the rated lightning impulse voltage shall be selected from the series in **6.1**(b) of IS : 2165-1977*.

APPENDIX A

(*Clauses* 3.5.1.6, 7.2.2.1, 7.2.2.2 *and* 7.2.2.3)

SURGE TRANSFERENCE THROUGH TRANSFORMERS

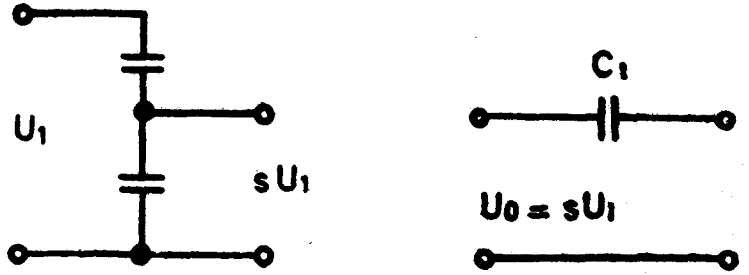
A-1. DERIVATION OF EXPRESSIONS

A-1.1 Initial Capacitive Voltage Spike — During the initial period of about one microsecond under the conditions of a lightning surge, the transformer may be approximately represented as shown in Fig. 13A as a capacitance voltage divider of ratio s where $s < 1$. If C_t is the sum of the capacitances of the higher-voltage and lower-voltage arms of this divider, the initial transference may be simulated as shown in Fig. 13B, 13C and 13D by a series circuit comprising a source $U_0 = sU_1$, a capacitance C_t and the capacitance or resistance of the external lower-voltage system. U_1 is the surge voltage on the higher-voltage side during the initial period. The source voltage U_0 is the open-circuit transferred voltage.

---

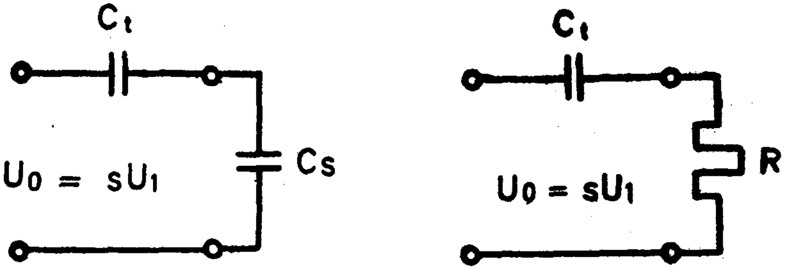
*Insulation co-ordination (*second revision*).

†Consider possible changes in line design such as tower footing and shielding wires, install surge arresters other than those intended to protect Case I apparatus, make use of protective spark gaps. The actual degree of protection provided by spark gaps is discussed in Appendix C.



13A Transformer as a Capacitive Voltage Divider

13B Equivalent Circuit of Capacitance Transmission



13C External System having Capacitance C_s

13D External System having Resistance R

FIG. 13 INITIAL CAPACITIVE VOLTAGE SPIKE

If the external system may be represented by a capacitance C_s as in Fig. 13C the equivalent circuit is a voltage divider having the ratio:

$$\frac{C_t}{C_t + C_s} \qquad \ldots \qquad (8)$$

If during the initial period, the impedance of the external system is the surge impedance of a cable or the resistance of the load, this system may be represented by a resistance R as shown in Fig. 13D. Typical values are from 10 ohms to a few hundred ohms. The transferred surge voltage is then dependent on the steepness as well as on the amplitude of the surge. For high values of R the initial voltage is approximately U_0 and for low values of R it is given approximately by $U_{2s} = s\ S\ R\ C_t$ where S is the maximum steepness of the surge.

The above expressions do not take into account the effect of superposition of the surge voltage on the power-frequency voltage.

Allowance may be made for the power-frequency voltage by substituting for U_1 the actual peak voltage U_p and by introducing the factor p. For a star/delta or delta/star connected transformer the value of p is typically about 1·15. For a star/star or delta/delta connected transformer the value of p is typically about 1·05. However, slightly higher values than these may be encountered. For switching surges the value of p may be taken as unity. The amplitude U_p will be limited to the front-of-wave sparkover value of the surge arrester or spark gap on the higher-voltage side of the transformer [*see* IS : 3070 (Part I)-1974*].

The amplitude of the initial voltage 'spike' on the lower-voltage side is given by:

$$U_{2s} = spU_p \qquad \dots \qquad \dots \qquad (9)$$

For a transformer without external connections to the lower-voltage terminals, the value of factor s may range from zero to at least 0·4, depending on the winding arrangement. The value of s may be measured in a low-voltage impulse response test (for example, with a recurrent-surge oscillograph). Values of C_t generally lie in the range 10^{-8} to 10^{-8} farad.

NOTE — The values of s and C_t are difficult to calculate for a new transformer and the manufacturer may only be expected to give a rough estimate without guarantee.

The value of U_{2s} should be compared with the appropriate impulse test voltage of Table 1, List 1 or 2, of IS : 2165-1977†.

The amplitude of the transferred surge may be reduced by:

a) Using a surge arrester with a lower front-of-wave sparkover voltage on the higher-voltage side,

b) Adding capacitance between each phase and earth on the lower-voltage side, and

c) Adding a surge arrester on the lower-voltage side between each phase and earth.

For numerical example *see* **A-2**.

A-1.2 Inductively Transferred Voltage — The transference of emf by inductive coupling between windings in a 3-phase transformer or bank of transformers may be evaluated for any winding connections by considering the surge voltage as a single-phase alternating voltage.

The effect of delta windings on the zero-phase-sequence component of the single-phase voltage should be taken into account.

---

*Lightning arresters for alternating current systems: Part I Non-linear resistor type lightning arresters.

†Insulation co-ordination (*second revision*).

Figure 14 shows the results for eight different connections of the transformer, assuming the system voltage ratio is unity.

As in the analogous power-frequency considerations the transferred voltages at the terminals are determined by the emf's and by voltage division between the internal impedance of the transformer and the external circuit impedance. The efm's may be assumed to have the same waveshape as the surge on the higher-voltage system, if the effects of internal oscillations in the windings are neglected. The response of the lower-voltage system to these emf's is usually in the form of a voltage of similar shape to the surge with a superposed oscillation.

The amplitude of the inductively-transferred voltage depends also on the voltage ratio and 3-phase connections of the transformer and on the relative impedances of the lower-voltage system and the transformer.

The voltage on the lower-voltage side of the transformer is given by:

$$U_2 = p\ q\ r\ U_p/N \quad \dots \quad \dots \quad (10)$$

where

q = is a response factor of the lower-voltage circuit to the transferred surge emf,

r = is a factor depending on the transformer connections (*see* Fig. 14),

U_p = is the peak voltage to earth on the higher-voltage side, and

N = is the system voltage (phase-to-phase) ratio of the transformer.

The value of q depends on the waveshape of the surge and on the electrical parameters of the lower-voltage circuit.

For lightning surges on a transfermer having Category 1 equipment without appreciable load connected to the lower-voltage side, the value of q is generally not greater than about 1·3 although this value may be exceeded. For switching surges on a similar system without appreciable load, the value of q is not greater than about 1·8.

Generally lower values of q apply if an appreciable load is connected due to voltage division between the load impedance and the leakage inductance of the transformer (*see* Note).

For Category 2 equipment, voltage division takes place between the leakage inductance of the transformer and the subtransient inductance of the generator, and if these are about equal, q has the value of about 0·9 for lightning and switching surges.

Values of r for a surge on one phase only (for example, a lightning surge) and for equal surges of opposite polarity on two phases (one type of switching surge) are shown in Fig. 14 for eight different 3-phase connections of the transformer.

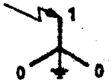
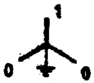
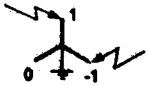
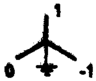
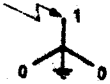
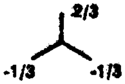
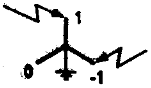
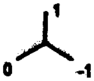
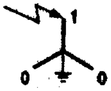
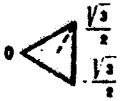
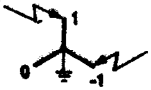
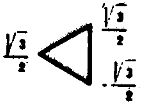
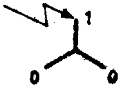
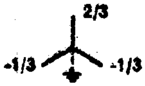
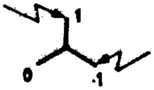
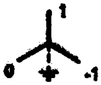
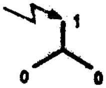
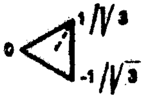
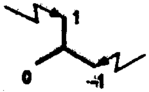
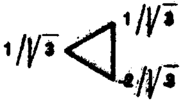
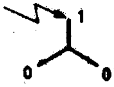
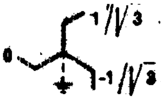
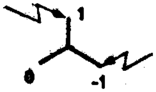
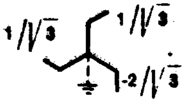
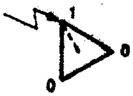
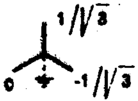
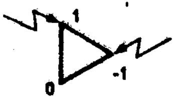
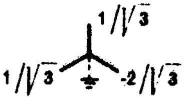
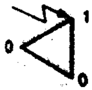
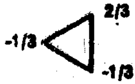
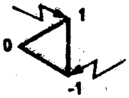
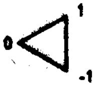
Case	Transformer connections			Surge on one phase only $U_A = 1,\ U_B = U_C = 0$		Surges of opposite polarity on 2 phases $U_A = 1,\ U_B = -1,\ U_C = 0$	
No	Higher-voltage winding	Lower-voltage winding	Tertiary	Higher-voltage winding	Lower-voltage winding	Higher-voltage winding	Lower-voltage winding
1	Y(e)	y (e)	(—, y)				
2	Y(e)	y (i)	(—, y)				
3	Y(e)	d	(—, y, d)				
4	Y(i)	y (e, i)	(—, y, d)				
5	Y(i)	d	(—, y, d)				
6	Y(i)	z (e, i)	(—, y, d)				
7	D	y (e, i)	(—, y, d)				
8	D	d	(—, y, d)				

FIG. 14 VALUES OF FACTOR ‘r’

As in the Original Standard, this Page is Intentionally Left Blank

The calculated value of U_2 is an estimate of the longer-duration transferred voltage, which in practice includes longer-term effects of capacitive transference and transferred voltages corresponding to internal oscillations within the windings. Its amplitude will be limited by the protective level of the surge arrester or protective spark gap. In the case of the former this will be the higher of the standard lightning impulse sparkover value and the residual voltage value for the lightning surges [*see* IS : 3070 (Part I)-1974*]. For switching surges, except when the transformer is connected to a highly-inductive load, such as an induction motor, over-voltages on the higher-voltage side may be assumed not to exceed per-unit overvoltage of 3 (*see* Note below).

The value of U_2 should be compared with the peak values of the appropriate power-frequency test-voltage of Table 1 of IS : 2165-1977†. It may be found necessary to reduce the value of the lightning or switching surge on the higher-voltage side of the transformer. Adding extra capacitance to the lower-voltage side has little effect upon the amplitude of the inductively-transferred voltage but it may be desirable to consider the addition of surge arrester.

NOTE — When the circuit is switched off on the higher-voltage side of a transformer which may be loaded on the lower-voltage side by reactors or other inductive load, then dangerous overvoltages may be attained under the most unfavourable conditions of operation but, in general, U_2 does not exceed the peak value of the power-frequency test voltage since q is less than 1·0 on account of voltage division between the transformer and the load inductance.

A-2. NUMERICAL EXAMPLES

A-2.1 Example A — Category 1 Installation

Transformer	145 kV star/12 kV delta	
Lightning impulse withstand voltage	145 kV side	= 550 kV
Impulse test voltage	12 kV side	= 60 kV (assuming List 1 of Table 1 of IS : 2165-1977†)
Power-frequency test voltage	12 kV side	= 28 kV

Surge arrester on higher-voltage side of the transformer:

Rated voltage = 120 kV

---

*Lightning arresters for alternating current systems: Part I Non-linear resistor type lightning arresters (*first revision*).

†Insulation co-ordination (*second revision*).

Front-of-wave sparkover voltage = 463 kV
1·2/50 impulse sparkover and residual voltage = 400 kV

a) *Lightning surge on one phase*

Initial voltage 'spike' for transformer disconnected from load:

$$U_{2s} = {}_{sp}U_p = 0{\cdot}4 \times 1{\cdot}15 \times 463 = 213 \text{ kV}$$

Assuming a ratio of 1·25 between the impulse withstand test voltage and the service overvoltage, that is, $\frac{60}{1{\cdot}25} = 48$ kV, would require the cable connections from the transformer to have a capacitance of:

$$\frac{C_t}{C_t + C_s} \leqslant \frac{48}{213} = 0{\cdot}23$$

hence $C_s > 3{\cdot}44\ C_t$

Having obtained from the transformer manufacturer a value of $C_t = 10^{-8}$ farad, the cable capacitance per phase should be at least $3{\cdot}42 \times 10^{-8}$ farad.

If the load is connected then this will reduce further the peak voltage on the lower-voltage side.

Due to inductive transference:

$$U_2 = pqr\ U_1/N$$

$$= \frac{1{\cdot}15 \times 1{\cdot}3 \times 0{\cdot}577 \times 400}{12{\cdot}1} = 28{\cdot}5 \text{ kV}$$

where

$$N = \frac{145}{12} = 12{\cdot}1$$

28·5 kV gives a ratio of 1·4 with the 39·6 kV peak test voltage ($28\sqrt{2}$) so that the insulation to Table 1 List 1 of IS : 2165-1977* shall be satisfactory.

b) *Switching surges of opposite polarity on two phases*

Assuming a p.u. switching overvoltage on two phases of 2·5, and $p = 1{\cdot}0$, $q = 1{\cdot}8$, and $r = \frac{2}{\sqrt{3}} = 1{\cdot}15$, then:

$$U_2 = \frac{1{\cdot}0 \times 1{\cdot}8 \times 1{\cdot}15 \times 145 \times \sqrt{2} \times 2{\cdot}5}{\sqrt{3} \times 12{\cdot}1}$$

$$= 50{\cdot}5 \text{ kV}$$

---

*Insulation co-ordination (*second revision*).

In this case the voltage peak exceeds the peak of the test voltage of 39·6 kV for Table 1 of IS : 2165-1977*. To allow for this either insulation for List 2 of the Table 1 of IS : 2165-1977* shall be used (that is, having test voltages of 75 kV lightning impulse withstand, and 28 kV rms/39·6 peak) or switching surges between phases on the higher-voltage transmission system shall be limited, alternatively a surge arrester may be selected on the higher-voltage side of the transformer having a lower protective level or consideration may be given to fitting a surge arrester on the lower-voltage side.

A-2.2 Example B — Category 2 Installation

A-2.2.1 *Typical Example for 220 kV Transformers*

245 kV star/24 kV	Delta generator transformer
Lightning impulse withstand voltage	245 kV side = 1 050 kV (Ref. Table 2 of IS : 2165-1977*)
Power-frequency test voltage	24 kV side = 50 kV
Impulse test voltage	24 kV side = 125 kV (Ref. List 2 of Table 1 of IS : 2165-1977*)

Surge arrester on higher-voltage side of transformer:

Rated voltage = 198 kV

Front-of-wave sparkover voltage = 746 kV

1·2/50 impulse sparkover and residual voltage = 649 kV

a) *Lightning surges on one phase*

Initial voltage 'spike' for transformer disconnected from 24 kV system:

$$U_{2s} = spU_p$$
$$= 0{\cdot}22 \times 1{\cdot}15 \times 746 = 189 \text{ kV (maximum)}$$

(the value for s having been obtained from the transformer manufacturer).

This value would obviously be too great for insulation on the lower-voltage side.

Assuming a ratio of 1·25 between the impulse test voltage and the service overvoltage, that is a value not exceeding 125/1·25 = 100 kV would require the addition of external capacitance. In this case:

$$\frac{C_t}{C_t = C_s} \leqslant \frac{100}{189} = 0{\cdot}53$$

hence $C_s > 0{\cdot}885\ C_t$

---

*Insulation co-ordination (*second revision*).

The value of C_t is obtained from the transformer manufacturer for a wave steepness $S = 1\,200$ kV/μs.

The other methods listed in this Appendix for reducing the capacitive peak (use of surge arresters) may also be considered.

The overvoltage due to inductive transference is:

$$U_2 = pqr\, U_1/N$$

$$= \frac{1{\cdot}15 \times 1{\cdot}0 \times 0{\cdot}577 \times 649}{10{\cdot}2} = 41{\cdot}5\ \text{kV}$$

41 kV is less than the 70·7 kV (50 $\sqrt{2}$) peak tests voltage, and this gives a ratio of 1·7, which can be considered adequate.

b) *Switching surges of opposite polarities on two phases*

Assuming a p.u. switching overvoltage on two phases of 2, then the inductive transference is:

$$U_2 = \frac{1{\cdot}0 \times 1{\cdot}0 \times 1{\cdot}15 \times 245 \times \sqrt{2} \times 2}{10{\cdot}5 \times \sqrt{3}} = 43{\cdot}5\ \text{kV}$$

where

$p = 1{\cdot}0$,

$q = 1{\cdot}0$, and

$$r = \frac{2}{\sqrt{3}} = 1{\cdot}15$$

43·5 kV is about equal to the inductive transference of lightning surge (41·5 kV).

A-2.3 Example C — Category 2 Installation

Typical Example for 300 kV Transformers

Delta generator transformer	300 kV star/24 kV	
Lightning impulse withstand voltage	300 kV side	= 1 050 kV
Power-frequency test voltage	24 kV side	= 50 kV
Impulse test voltage	24 kV side	= 125 kV (assuming List 2 of Table 1 of IS : 2165-1977*)

Surge arrester on higher-voltage side of transformer:

Rated voltage = 240 kV

Front-of-wave sparkover voltage = 900 kV

1·2/50 impulse sparkover and residual voltage = 785 kV

---

*Insulation co-ordination (*second revision*).

a) *Lightning surge on one phase*:

Initial voltage 'spike' for transformer disconnected from 24 kV system:

$$U_{2s} = spU_p$$
$$= 0{\cdot}2 \times 1{\cdot}15 \times 900 = 207 \text{ kV maximum,}$$

the value for s having been obtained from the transformer manufacturer. This would obviously be too much for the insulation on the lower-voltage side.

Assuming a ratio of 1·25 between the impulse-withstand test voltage and the service overvoltage that is a value not exceeding 125/1·25 = 100 kV, would require the addition of external capacitance.

In this case $\frac{C_t}{C_t + C_s} \leqslant \frac{100}{207} = 0{\cdot}48$

Hence $C_s \geqslant 1{\cdot}08\, C_t$

The value of C_t is obtained from the transformer manufacturer for a steepness S = 1 200 kV per microsecond [*see* IS : 3070 (Part I)-1974*].

Alternatively the other methods listed in this appendix could be considered.

Due to inductive transference:

$$U_2 = pqr\, U_1/N$$
$$= \frac{1{\cdot}15 \times 1{\cdot}0 \times 0{\cdot}577 \times 785}{12{\cdot}5} = 41{\cdot}4 \text{ kV}$$

41·4 kV is less than 70·7 kV_p ($50\sqrt{2}$) test voltage and this gives a ratio of 1·7 which may be considered adequate.

b) *Switching surges of opposite polarity on two phases*:

Assuming a p.u. switching overvoltage on two phases of 2, then the inductive transference is:

$$U_2 = \frac{1{\cdot}0 \times 1{\cdot}0 \times 1{\cdot}15 \times 300 \times \sqrt{2} \times 2}{12{\cdot}5\sqrt{3}}$$
$$= 45 \text{ kV}$$

where

$p = 1{\cdot}0$,
$q = 1{\cdot}0$, and
$r = \frac{2}{\sqrt{3}} = 1{\cdot}15$

45 kV is about equal to the inductive transference of lightning surge (41·4 kV).

---

*Lightning arresters for alternating current systems: Part I Non-linear resistor type lightning arresters (*first revision*).

APPENDIX B

(*Clause* 4.1.2)

VALIDITY OF SWITCHING AND LIGHTNING IMPULSE WITHSTAND TESTS, 50 PERCENT DISRUPTIVE DISCHARGE TEST AND 15 IMPULSES WITHSTAND TEST

B-1. CONFIDENCE LIMITS OF THE TEST

Tests may provide only more or less accurate estimates of the true values of the withstand strength of equipment.

An increase in the accuracy may be obtained by an increase in the extent of the test. The extent of tests must, however, be limited for reasons of costs, the diminishing return of gain in the accuracy and possible destructive effects on the equipment. For these reasons IS : 2165-1977* prescribes three different test methods in **7.2**, **7.3** and **7.4** according to the type of equipment.

In **7.3** (a) dealing with the 50 percent disruptive discharge test, the note states that ' There are a number of procedures available, and any of these may be used provided that the accuracy of the determination is within one half of the standard deviation with a confidence level of 95 percent '. It can be said that there should be a 95 percent probability that the 50 percent discharge voltage of the equipment at the time of the test be within the boundaries given by the value estimated from the test plus and minus one half of the standard deviation.

A test procedure fulfilling this requirement is the ' up and down ' test with 30 shots.

The accuracy of the 15 impulse withstand test is considerably less. The 95 percent confidence limits for the probability of discharge are in this test:

For	0	discharges	approximately	0	to	0·213
,,	1	,,	,,	0	,,	0·32
,,	2	,,	,,	0·015	,,	0·40
,,	3	,,	,,	0·045	,,	0·48
,,	4	,,	,,	0·08	,,	0·54
,,	5	,,	,,	0·12	,,	0·61

Based on 95 percent confidence limits, it may be seen that from a test with 15 impulses only, it is not possible to conclude that the discharge

---

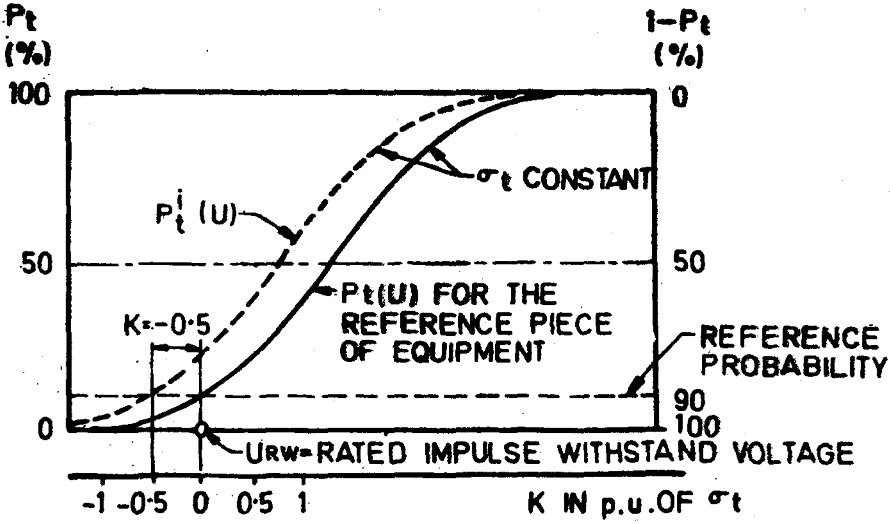
*Insulation co-ordination (*second revision*).

probability is less than 0·10, or that the probability of withstand is higher than 0·90, even for 0 discharge. When the number of discharges exceeds 4, the test is significant as a test of the hypothesis that the probability of withstanding is less than 0·90.

B-2. EXAMINATION OF DIFFERENT METHODS OF TEST

Accepting the above basic limitations of tests with a small number of impulses, the following exposes the validity of different methods of discharge testing and the balance between the risks to the manufacturer and the purchaser bearing in mind the practical necessity for a limited number of impulses and, for the manufacturer, to design his products to have an economically acceptable risk of failure on tests.

For the sake of simplicity it is assumed in this appendix that the discharge probability P_t (U) of the different pieces of equipment in a given population (same type of equipment on which an impulse test is to be carried out) follows a Gaussian law with a constant standard deviation σ_t equal for all the pieces of equipment. In this case one parameter (K given in p.u. of σ_t, *see* Fig. 15) is sufficient to determine the deviation of the insulation strength of one piece of equipment '*i*' at the time *t* (U_{t90}) from the specified value (U_{RW}).



$$K = \frac{U_{t90} - U_{RW}}{\sigma_t}$$

Fig. 15 Definition of the Insulation Strength of a Piece of Equipment at the Time *t* as Function of the Parameter *K*

The 90 percent withstand strength of a piece of equipment in a population varies from one specimen to another. Fig. 16 shows how this may be described statistically in terms of K. The value of σ_p is very small for those types of equipment (for example, disconnectors) which may be considered essentially air insulating structures, since tolerances in dimensions are always very small.

To ensure the repeatability of tests, ambient and insulation conditions should be kept as constant as possible during test (or correction factors should be used) and standardized testing techniques should be adopted. In principle, therefore, the discharge probability of a given piece of insulation under test conditions should not be expected to change. In other words the $P_t^i(U)$ (*see* Fig. 15) should be the same in different tests of the same type.

However the value of the 90 percent withstand strength of insulation may show variations from the average value derived from several tests by the same methods carried out in the same laboratory at different times or in different laboratories, due to differences in the ambient and insulation conditions or in the test circuits. How the laboratory inaccuracy can be described statistically considering the average value of the insulation strength of one specimen as the ' true value ' is shown in (b) in Fig. 16.

Assuming that the distributions in (a) and (b) in Fig. 16 are Gaussian with known standard deviations and that the design value of U_D has been chosen by the manufacturer, the probability density of the deviation of the measured 90 percent withstand strength of the population of a piece of equipment may be calculated [*see* (c) in Fig. 16].

An ideal test should be such as to prevent equipment having, at the time of the test, either an insulation withstand lower than prescribed to pass the test or an insulation withstand equal to, or higher than prescribed to fail.

Self-restoring insulation having, at the rated impulse withstand voltage applied during the test, a probability of withstand equal to, or higher than, the reference probability (90 percent) should have a probability of passing the test equal to 1, while insulation having a probability of withstand lower than the reference probability should have no chance of passing the test.

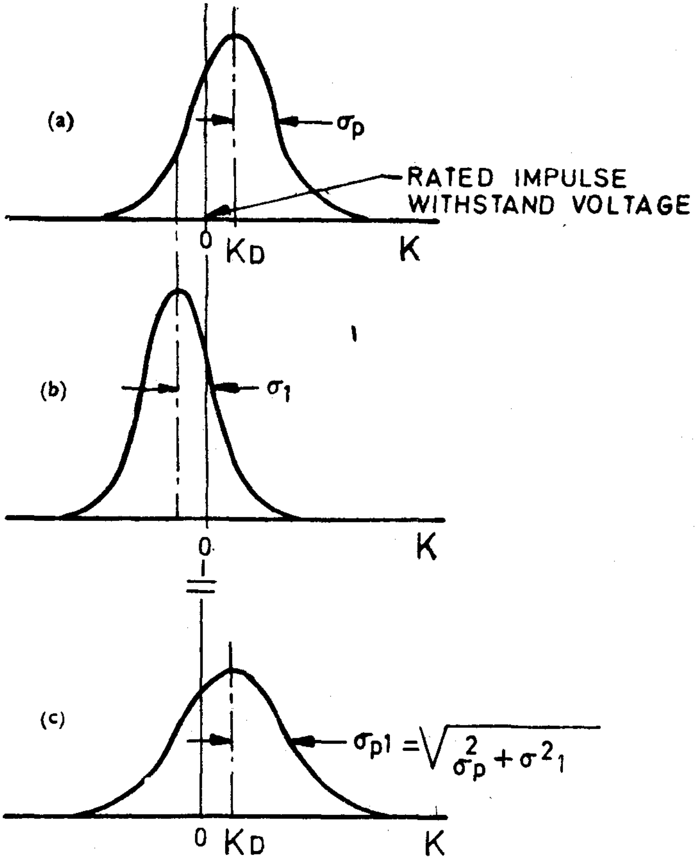
The probability of passing an ideal test of an apparatus, the insulation of which, during the test, differs by K from the prescribed value, is represented in Fig. 17 as a function of K by the solid line.

Actual test, however, depart from the ideal test and follow in the (Q, K) plane curves similar to the dashed line.

Figure 17 shows the curves for the tests proposed in **7.2**, **7.3** and **7.4** of IS : 2165-1977*. As far as the test of **7.3** is concerned an ' up and down ' test based on 30 shots was taken into consideration.

---

*Insulation co-ordination (*second revision*).



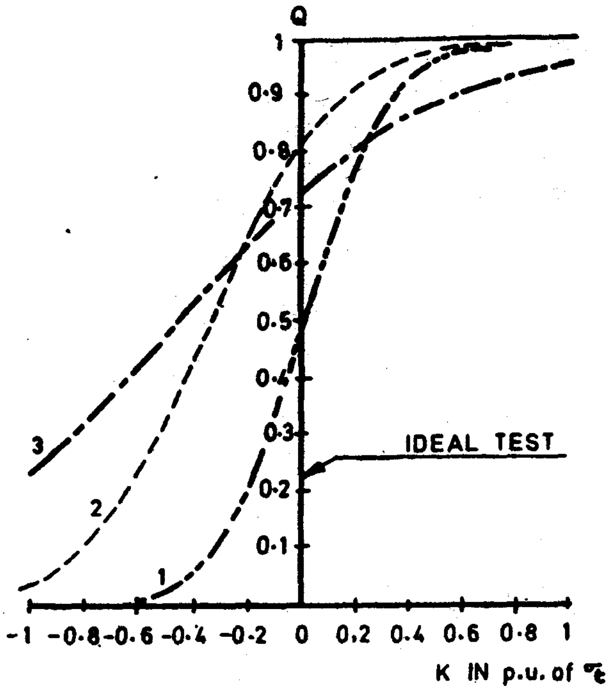
a) Distribution of the 90 percent withstand voltage of the apparatus of population *p*.

b) Distribution of the difference between the 90 percent withstand voltage of a given apparatus measured in various laboratories and the actual one.

c) Distribution of the 90 percent withstand voltage of any apparatus of population *p* in various laboratories.

FIG. 16 FREQUENCY DENSITY OF THE MEASURED 90 PERCENT WITHSTAND STRENGTH OF A POPULATION OF APPARATUS

The probability density of the deviation of the measured withstand strength [*see* (c) in Fig. 16] of a given population is represented in Fig. 18 by Curve 1. By multiplication of the values of this curve by the value of the probability of passing a given test procedure as a function of *K* (*see* Fig. 17) Curve 2 is obtained. This curve represents the density distribution of the



1 = Up and down test 30 impulses (**7.2** of IS : 2165-1977*)

2 = 15/2 test (**7.3** of IS : 2165-1977*)

3 = 3/0 test (**7.4** of IS : 2165-1977*)

*Insulation co-ordination (*second revision*).

FIG. 17 PROBABILITY OF AN EQUIPMENT TO PASS THE DIFFERENT TYPE OF TEST AS A FUNCTION OF ITS INSULATING CHARACTERISTICS

accepted deviation *K* of the population of apparatus for the given test procedure.

If the area limited by Curve 1 and its abscissa is taken equal to 1, Area *A* in Fig. 18 represents probability R_m of rejection of a good product (manufacturer's risk) while Area *B* represents the probability of rejection of a deficient product. As a matter of fact the intended value of insulation design *W* will be chosen by the manufacturer on the basis of the sum of Areas *A* and *B*, that is, on the probability P_f of failing the test. Area *C* represents the probability R_c of acceptance of a deficient product (customer's risk). By repeated calculation of R_c and P_f for different values of

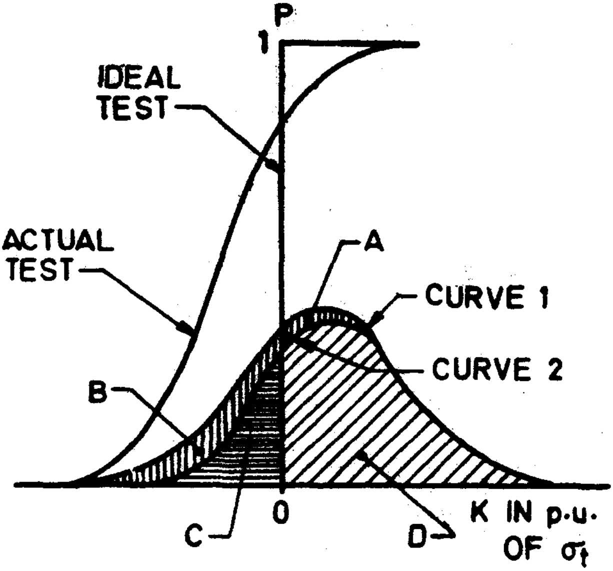


FIG. 18 PROBABILITY P_f OF TEST FAILURE (AREA A + B)
MANUFACTURER'S RISK R_m (AREA A)
CUSTOMER'S RISK R_c (AREA C)

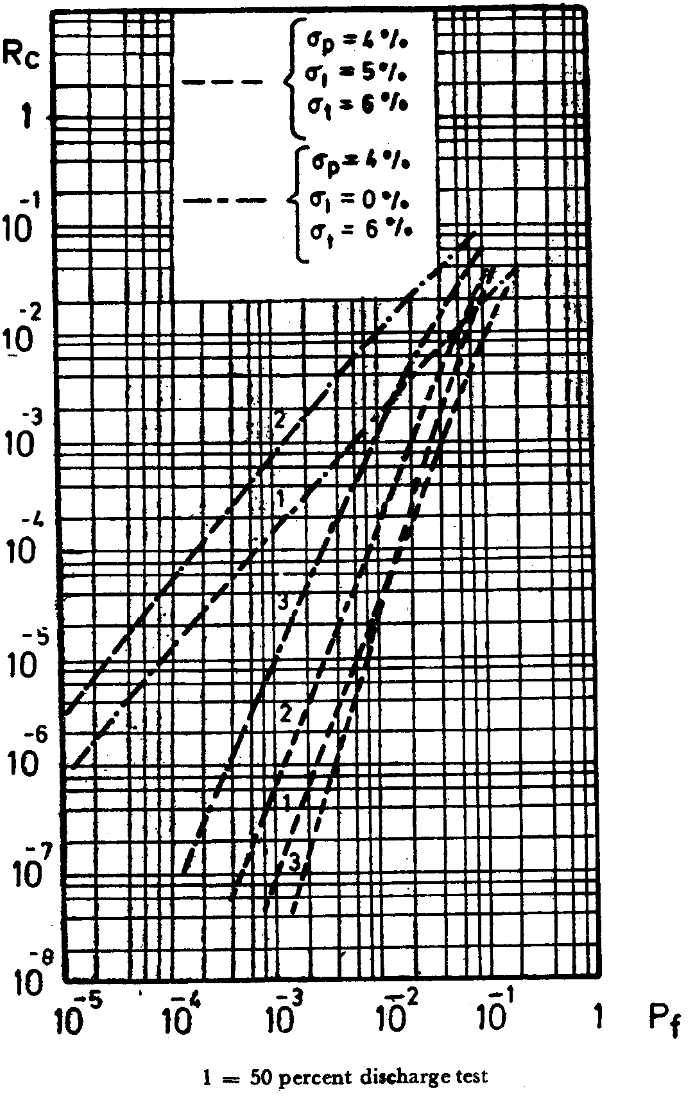
the intended value of the insulation strength (*W*), curves can be constructed which show the relation between the risk of the user to accept a deficient product and the manufacturer's probability P_f of failing the test.

Figure 19 shows such curves on the assumption that standard deviations σ_p, σ_l and σ_t are those stated in the figures.

Figure 20 gives the correlation between R_m (manufacturer's risk) and R_c (customer's risk) for the cases considered in Fig. 19.

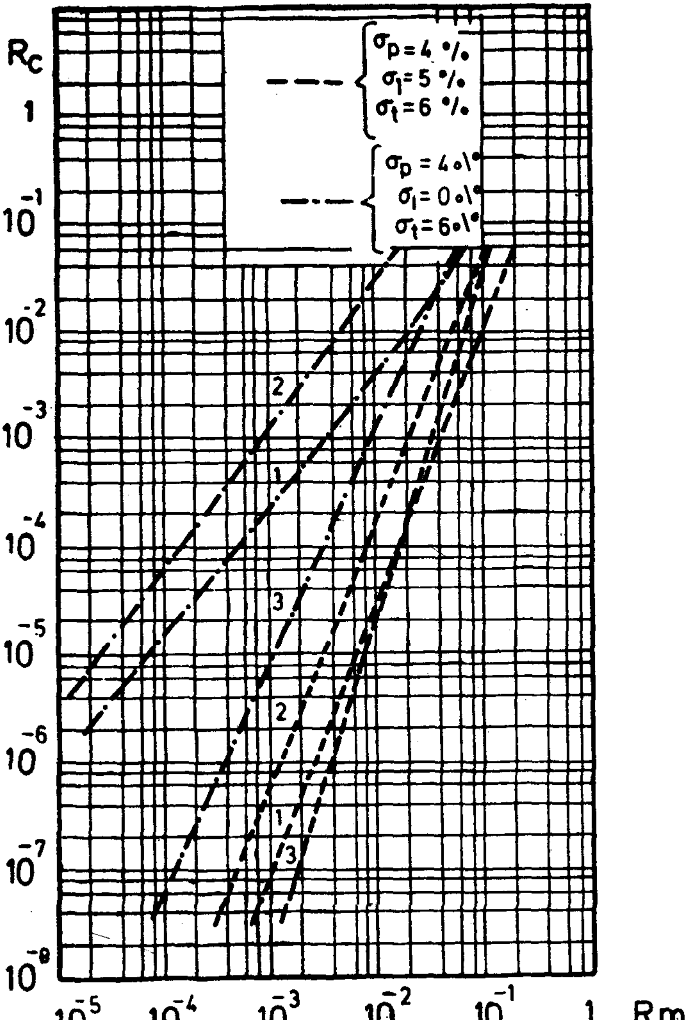
It is to be noticed that if σ_p and σ_l are zero (homogeneous population and no laboratory inaccuracy) one of the two values R_m and R_c is zero.

In other words there is only a risk either for the user or for the manufacturer. This risk as well as the value of P_f may be obtained directly from Fig. 17.



1 = 50 percent discharge test
2 = 15/2 test
3 = 3/0 test

FIG. 19 CUSTOMER'S RISK R_c AS A FUNCTION OF PROBABILITY P_f TO FAIL THE TEST



1 = 50 percent discharge test
2 = 15/2 test
3 = 3/0 test

FIG. 20 CUSTOMER'S RISK R_c AS A FUNCTION OF MANUFACTURER'S RISK R_m

APPENDIX C

(*Clauses* 5.4.1, 5.5.3 *and* 9.2.2)

STATISTICAL EVALUATION OF THE PROTECTIVE EFFECT OF SPARK GAPS

C-1. For a given waveshape of the applied impulse, let us call:

a) P_i (U) and P_p (U) the disruptive discharge probabilities of the insulation and of the spark gap as a function of the crest value U of the impulse*.

b) P_{ip} (U) the probability that the insulation may discharge before the protective gap sparkover as a function of the crest value U of the impulse.

The discharge probability curves of insulation P_i (U) and of the spark gap P_p (U) connected in parallel are expressed by:

$$P_i(U) = P_i(U).\,[\,1 - P_p\,(U)\,] + P_i\,(U)\,P_p\,(U)\,P_{ip}\,(U) \qquad \ldots(11)$$

$$P_p\,(U) = P_p\,(U).\,[\,1 - P_i(U)\,] + P_p\,(U)\,P_i\,(U)\,[\,1 - P_{ip}\,(U)\,] \qquad \ldots(12)$$

NOTE — On the assumption that times-to-discharge of the insulation and of the spark gap follow a Gaussian law, whatever may be the crest value U of the applied impulse, P_{ip} (U) is expressed by:

$$P_{ip}\,(U) = \tfrac{1}{2} - \frac{1}{\sqrt{2\pi}} \int_{0}^{T_{ip}(U)} \text{exp.} \left(-\frac{t^2}{2}\right) dt \qquad \ldots(13)$$

where

$$T_{ip}\,(U) = \frac{T_i\,(U) - T_p\,(U)}{\sqrt{\sigma_{ti}^2\,(U) + \sigma_{tp}^2\,(U)}}$$

T_p (U) is the 50 percent value of the time-to-sparkover of the spark gap, as a function of the crest value U of the applied impulse;

T_i (U) is the 50 percent value of the time-to-discharge of the insulation, as a function of the crest value U of the applied impulse;

σ_{tp} (U) is the standard deviation of the time-to-sparkover of the spark gap, as a function of the crest value U of the applied impulse; and

σ_{ti} (U) is the standard deviation of the time-to-discharge of the insulation, as a function of the crest value of the applied impulse.

If, for a particular combination of the insulation to be protected and of the spark gap, there is a negligible probability that the time-to-discharge of equipment may be lower than the time-to-sparkover of the gap in the entire range $0 < U < U_{max}$, P_{ip}. (U) becomes zero and formula (11 may be written:

$$P_i(U) = P_i(U)\,[\,1 - P_p\,(U)\,] \qquad \ldots(14)$$

---

*The formulae given below are generally valid for two pieces of insulation in parallel.

In the case of combinations of insulation and protective gaps of this kind, we shall consider the behaviour of the protective gap as being 'ideal'.

By making use of formula (7), the risk of failure of a protected piece of insulation can be evaluated by means of the following formula:

$$R_i = \int_0^{U_{max}} P_i(U)\,[\,1 - P_p(U)\,]\, f_0(U)\, dU + \int_0^{U_{max}} P_i(U).\, P_p(U)\, P_{ip}(U).f_0(U)\, dU \qquad ...(15)$$

If the protective gap can be considered 'ideal', the second term in formula (15) is equal to zero, and we obtain the following formula:

$$R_i = \int_0^{U_{max}} P_i(U).[\,1 - P_p(U)\,]\, f_0(U)\, dU \qquad ...(16)$$

The ratio of the 50 percent lightning impulse sparkover voltage to the 50 percent switching impulse sparkover voltage of a spark gap can be chosen from a wide range (1 ÷ 1·5) by changing the electrode configuration. It is, therefore, possible to select the discharge probability curve of the gap P_p (U) to switching impulses quite irrespective of the discharge probability curve to lightning impulses.

Design of a spark gap with a view to switching impulse will make the average expected number of flashovers of the gap per year, due to switching surges, equal to a value N_s such as not to make system performance under switching surge significantly worse. Therefore, the probability of sparkover of the gap due to switching overvoltages reaching the level evaluated on the assumption that equipment operates as designed (*see* **9.3**) shall be very low.

Consequently, even if the spark gap behaves like an 'ideal' protective device, the spark gap will provide no protection against them and insulation shall be designed to withstand this type of switching overvoltages. This is evident from formula (14) (case of ideal spark gap).

$$P_i = P_i(\,U\,).\ [\,1 - P_p(\,U\,)\,] \simeq P_i(\,U\,) \qquad ...(17)$$

As regards switching overvoltages exceeding the values based on the assumption of correct behaviour of equipment, we can assume that the overvoltage value is such that a gap sparkover will almost certainly be caused and formula (11) then becomes:

$$P_i(\,U\,) = P_i(\,U\,)\ P_{ip}(\,U\,) \qquad ...(18)$$

and formula (15)

$$R_i = \int_{0}^{U_{max}} P_i\ (U)\ P_{ip}\ (U)\ f_0\ (U).\ dU \qquad \ldots(19)$$

The protective effect is, in this case, due only to $P_{ip}\ (U)$ that is, to the relationship between the time-to-discharge of the insulation and those of the gap. It is, therefore, necessary to make $P_{ip}\ (U)$ as close as possible to zero over the entire range of interest of U.

Design of a spark gap with lightning impulses in view will be such as to limit the average expected number of flashovers per year of the gap to lightning surges to an acceptable value $\overline{N}_1$.

In this connection, it shall be remembered that in many cases the sparkover of the gap does not lead to any supply interruption.

Let us consider the example of a spark gap installed on the line side of the breaker. If the lightning stroke causes the line to flashover, a coincidental sparkover of the gap is of no significance. On the other hand, if the overvoltage amplitude does not reach the sparkover level of the line at the point struck, it is unlikely to cause a sparkover of the gap, even if the gap withstand level is lower than that of the line. This is due to the reduction in surge amplitude at the point of installation of the spark gaps, because of attenuation as well as the possible presence of other lines and surge arresters at the station.

Thus, in contrast to the case of switching surges, it is possible to accept in certain cases spark gaps with a 50 percent discharge voltage to lightning impulses lower than that obtained, basing the design of the apparatus on switching surges and using the combination of the rated impulse withstand voltages given in Table 3 of IS : 2165-1977*.

Therefore, it may be concluded from formulae 11 and 14 that spark gaps may offer a limited degree of protection in the case of lightning overvoltages of the order of the rated lightning impulse withstand voltage of the apparatus.

As regards lightning overvoltages much higher than the rated lightning impulse withstand voltage of the apparatus gap sparkover will almost certainly be caused. In this case formula 18 and the same considerations as regards $P_{ip}\ (U)$ previously made in respect of switching surges apply.

For air insulation of equipment the condition $P_{ip}\ (U) \simeq 0$ may be fulfilled both for lightning and switching impulses by making use of gaps having a high critical sparkover voltage to switching surges (kV/cm), that

---

*Insulation co-ordination (*second revision*).

is, gaps much shorter than air distances of the apparatus, for instance by making use of spark-gaps having a conductor-rod configuration for the electrodes.

For non-self-restoring insulation of equipment the check that factor P_{1p} (U) is reasonably small should be made by means of chopped wave withstand test carried out at a voltage level based on the highest overvoltage which may be expected in the system and with a truncation time to be chosen on the basis of the time-to-sparkover of the gap.

These tests are not laid down in IS : 2165-1977* and, if necessary should be agreed upon between the user and the supplier.

APPENDIX D

(*Clause* 9.3)

EXAMPLES OF APPLICATION

D-1. Table 3 illustrates the choice of the insulation level of a piece of equipment for Case I (*see* **9.3**) protected against both switching and lightning overvoltages by surge arresters mounted at its terminals. Example 1 refers to 420 kV transformer and Example 2 to a 765 kV transformer.

D-2. The insulation levels of the transformers depend on the protective levels of arresters against both switching and lightning impulses (Block 7 of Fig. 12). The protection level of a particular surge arrester depends, in its turn, on its characteristics and rating. The rating of surge arresters in both Examples 1 and 2 is chosen as the available rating immediately above the temporary overvoltages anticipated on the system (Block 6). Temporary overvoltages include voltage rise during faults, overvoltages due to inrush currents, sudden load rejection and other causes. The overvoltage to be expected is influenced by the earth fault factor, system configuration, the characteristics of system equipment, and operating practices (*see* **3.3**).

D-3. Table 4 shows the choice of the insulation level of a piece of equipment for Case II with no surge arrester protection or with remote surge arrester protection. Example 1 refers to the line-to-earth insulation of a 420 kV disconnecting switch on the line-side of the breaker, no surge arresters being installed at the line entrance. Example 2 refers to a 765 kV disconnecting switch at the same location.

D-4. The rated switching impulse withstand voltage is selected first from Table 3 of IS : 2165-1977* on the basis of the statistical switching overvoltage level at the equipment location and on the basis of an acceptable risk of failure (Blocks 4 and 8 of Fig. 12).

---

*Insulation co-ordination (*second revision*).

TABLE 3 CHOICE OF THE INSULATION LEVEL OF CASE I EQUIPMENT (FOR EXAMPLE TRANSFORMER PROTECTED BY SURGE DIVERTERS)

(*Clause* D-1)

	UNIT	EXAMPLE 1	EXAMPLE 2
1) *Basic Data*			
Highest voltage for equipment U_m (rms)	kV	420	765
Corresponding line-to-ground voltage:			
rms value	kV	243	442
Peak value $U_m\sqrt{2} / \sqrt{3}$	kV (p.u.)	343 (1·00)	625 (1·00)
Determining temporary overvoltage (derived from system studies):			
rms value	kV	320	605
Peak value	kV (p.u.)	452 (1·32)	855 (1·37)
Minimum safety factor.			
For switching overvoltages.	—	1·15	1·15
For lightning overvoltages	—	1·25	1·25
2) *Representative Characteristics of Surge Arrester*			
Rated voltage (rms)	kV	324	612
Max switching impulse sparkover voltage	kV	765	1 230
Max lightning impulse sparkover voltage	kV	805	1 400
Max front-of-wave sparkover voltage	kV	1 010	1 660
Max residual voltage at rated discharge current	kV	735	1 400
3) *Protection Level:*			
To switching impulses	kV (p.u.)	765 (2·23)	1 230 (1·96)
To lightning impulses	kV (p.u.)	878* (2·56)	1 440* (2·30)
4) *Insulation Level (Phase-to-Earth) Switching Impulses*			
Minimum conventional switching impulse withstand voltage	kV (p.u.)	880 (2·66)	1 415 (2·26)
Rated switching impulse voltage	kV (p.u.)	950 (2·77)	1 425 (2·28)
Ratio of the rated switching impulse withstand voltage to the switching impulse protection level	—	1·24	1·16
Lightning Impulses:			
Minimum conventional lightning impulse withstand voltage	kV (p.u.)	1 100 (3·20)	1 800 (2·76)
Rated lightning impulse withstand voltage	kV (p.u.)	1 175 (3·42)	1 800 (2·87)
Ratio of the rated lightning impulse withstand voltage to the lightning impulse protective level	—	1·33	1·25

NOTE — State Electricity Boards with 420 kV power system are requested to provide the details for Example 1 in accordance with the practices they are following in their system.

*Maximum front-of-wave sparkover divided by 1·15 (*see* 5.2.1).

TABLE 4 CHOICE OF THE INSULATION LEVEL OF CASE II EQUIPMENT (FOR EXAMPLE UNPROTECTED DISCONNECTING SWITCH)

(*Clause* D-3)

	UNIT	EXAMPLE 1	EXAMPLE 2
Basic Data			
Highest voltage for equipment U_m (rms)	kV	420	765
Corresponding line-to-ground voltage:			
rms value	kV	243	442
Peak value $U_m\sqrt{2} / \sqrt{3}$	kV (p.u.)	343 (1·00)	625 (1·00)
Statistical overvoltage at the equipment location (value exceeded in 2 percent of cases only) due to reclosing operations	kV (p.u.)	910 (2·65)	1 255 (2·0)
Maximum accepted risk of flashover to ground for reclosing operation	—	10^{-3}	10^{-4}
Statistical safety factor γ corresponding to the maximum accepted risk of flashover (derived from Fig. 7)	—	1·13	1·24
Minimum statistical switching impulse withstand voltage	kV	1 030	1 550
Rated switching impulse withstand voltage selected	kV	1 050	1 550
Risk of flashover corresponding to the rated switching impulse withstand voltage selected	—	$4 \cdot 10^{-4}$	10^{-4}
Recommended rated lightning impulse withstand voltage to be associated with the rated switching impulse withstand voltage	kV (p.u.)	1 425 (4·15)	2 400 (3·84)

For both examples, it is assumed that the only critical switching overvoltages are those due to line re-energization (that is, it is necessary to check the risk of failure due to reclosing operations only).

By making use of the simplified statistical approach (*see* **9.2.3**) and choosing an appropriate standard deviation it is possible to determine the statistical safety factor γ corresponding to the maximum admissible risk of flashover; from factor γ it is possible to derive the minimum statistical switching impulse withstand voltage and then to select the rated switching impulse withstand voltage immediately above.

In the example the correlation between risk of failure and statistical safety factor given in Fig. 7 (σ_T = 8 percent) is used.

D-5. Once the rated switching impulse withstand voltage has been obtained, a corresponding rated lightning impulse withstand voltage is selected from the same line of Table 3 of IS : 2165-1977* considering that only the highest value of rated lightning impulse withstand voltage should be used for apparatus not effectively protected by surge diverters (*see* **6.4** of IS : 2165-1977*).

It is then necessary to verify that this value guarantees a satisfactory performance under atmospheric overvoltages, that is, a risk of failure not

---

*Insulation co-ordination (*second revision*).

higher than the permissible one. This can be done in a similar way as previously for switching surges (Blocks 9 to 12 in Fig. 12).

In the case under consideration an approximate distribution of the lightning overvoltages, at least for the case of disconnecting switches in the open position, may be evaluated quite simply on the basis of the line characteristics and of empirical or semi-empirical laws for wave attenuation.

However, lightning overvoltage stresses vary from point to point in a substation. In general, it is therefore extremely difficult and time consuming to achieve the necessary knowledge of stresses by making use of the statistical or simplified statistical approach.

Only the highest overvoltage stresses in the most common contingencies (most common position of breakers and disconnectors) are therefore evaluated. It is then verified that the rated lightning impulse withstand voltage selected, as said above starting from the rated switching impulse withstand voltage, exceeds the maximum credible atmospheric overvoltages by a suitable margin (≅ 10 percent). If a rated lightning mpulse voltage higher than the one determined on the basis of Table 3 of IS : 2165-1977* is desirable, the value shall be selected from the series in **6.1** (b) of IS : 2165-1977*.

D-6. In Table 5 there is an evaluation of the increase of the risk of failure for the rated switching impulse withstand voltage lower than the selected value given in Table 3 of IS : 2165-1977*.

TABLE 5 RISK OF FAILURE OF INSULATION AS A FUNCTION OF THE RATED SWITCHING IMPULSE WITHSTAND VOLTAGES OF THE EQUIPMENT OF TABLE 4

	UNIT	EXAMPLE 1	EXAMPLE 2
Alternative (*a*)			
Rated switching impulse withstand voltage (selected value)	kV (p.u.)	1 050 (3·06)	1 550 (2·48)
Statistical safety factor	—	1·16	1·24
Risk of failure corresponding to the above statistical safety factor	—	$4 \cdot 10^{-4}$	10^{-4}
Alternative (*b*)			
Rated switching impulse withstand voltage	kV (p.u.)	950 (2·76)	1 425 (2·28)
Statistical safety factor	—	1·05	1·14
Risk of failure	—	$5 \cdot 10^{-3}$	$9 \cdot 10^{-4}$
Alternative (*c*)			
Rated switching impulse withstand voltage	kV (p.u.)	—	1 300 (2·08)
Statistical safety factor	—	—	1·04
Risk of failure	—	—	$6 \cdot 10^{-3}$

---

*Insulation co-ordination (*second revision*).

APPENDIX E

(*Clause* 9.3)

CLEARANCES IN AIR BETWEEN LIVE CONDUCTIVE PARTS AND EARTHED STRUCTURES TO SECURE A SPECIFIED IMPULSE WITHSTAND VOLTAGE FOR DRY CONDITIONS

E-1. In installations which, for various reasons, may not be impulse tested, it is advisable to take steps to avoid flashover occurring below the impulse withstand level which would have been prescribed in the case of a test.

E-2. The condition to be fulfilled is that the statistical switching and lightning impulse withstand voltages in air between live parts and earth should be equal to the rated switching and lightning impulse withstand voltage as specified in IS : 2165-1977*. This results in a minimum clearance to be observed which depends on the configuration of the live parts and the nearby structures (electrode configuration).

E-3. No distance is indicated for an equipment which has an impulse test included in its specification since compulsory clearances might hamper the design of the equipment, increase its cost and impede progress. The impulse test, even when only a type test, is sufficient to prove that the impulse withstand condition is fulfilled.

E-4. Table 6A and 6B are suitable for general application, providing as a first approximation a clearance to be specified in relation to the insulation level. These tables have been compiled for easy use.

E-4.1 In Table 6A ($U_m \leqslant 245$ kV) reference is made in the first column to the rated lightning impulse withstand voltage and in the second column to the air clearances for unfavourable configurations of live and earthed parts.

E-4.2 In Table 6B ($U_m \geqslant 245$ kV) reference is made in the col (1) and (2) to the values defining the insulation levels and in the col (3) and (4) to air-clearances for electrode configurations of the ' conductor-structure ' type and ' rod-structure ' type.

E-5. The ' rod-structure ' configuration is the worst electrode configuration normally encountered in practice; the ' conductor-structure ' configuration covers a large range of normally used configurations. In Table 6B reference is made to the electrode configuration because of its notable influence for $U_m > 245$ kV.

E-6. The values of air clearances given in Table 6 are the minimum values selected by electrical considerations, and do not include any addition for construction tolerances, effect of short-circuits, safety of personnel, etc.

These values are valid for altitudes not exceeding 1 000 m.

---

*Insulation co-ordination (*second revision*).

TABLE 6A CORRELATIONS BETWEEN INSULATION LEVELS AND MINIMUM PHASE-TO-EARTH AIR CLEARANCES

(*Clause* E-4)

RATED LIGHTNING IMPULSE WITHSTAND VOLTAGE (1)	MINIMUM PHASE-TO-EARTH AIR CLEARANCE (2)
kV	mm
45	60
60	90
75	120
95	160
125	220
170	320
325	630
380	750
450	900
550	1 100
650	1 300
750	1 500
850	1 600
950	1 900
1 050	2 400

TABLE 6B CORRELATIONS BETWEEN INSULATION LEVELS AND MINIMUM PHASE-TO-EARTH AIR CLEARANCES

(*Clause* E-4)

IMPULSE WITHSTAND VOLTAGES		MINIMUM PHASE-TO-EARTH AIR CLEARANCE	
Rated Switching Impulse Withstand Voltage	Rated Lightning Impulse Withstand Voltage	Conductor-Structure	Rod-Structure
(1)	(2)	(3)	(4)
kV	kV	m	m
750	850	1·6	1·9
750	950	1·7	1·9
850	950	1·8	2·4
850	1 050	1·9	2·4
950	1 050 ; 1 175	2·2	2·9
1 050	1 175 ; 1 300 ; 1 425	2·6	3·4
1 175	1 300 ; 1 425 ; 1 550	3·1	4·1
1 300	1 425 ; 1 500 ; 1 800	3·6	4·8
1 425	1 550 ; 1 800 ; 2 100	4·2	5·6
1 550	1 800 ; 1 950 ; 2 400	4·9	6·4

PRINTED AT SIMCO [illegible] PRESS, DELHI [illegible]IA)

AMENDMENT NO. 2 APRIL 1985

TO

IS : 3716 - 1978 APPLICATION GUIDE FOR INSULATION CO-ORDINATION

(First Revision)

Alteration

(*Page* 8, *clause* 1.2, *line* 1) — Delete the word ‘ only ’.

Addenda

(*Page* 8, *clause* 1.2) — Add the following new clause after the existing and renumber the subsequent clause:

‘ **1.3** This guide also covers guidance on phase-to-phase insulation co-ordination the principles and rules for which are enumerated in IS : 2165 (Part 2)-1983* (*see* Appendix F). ’

(*Page* 88, *Appendix E*) — Add the following Appendix after the existing:

APPENDIX F

(*Clause* 1.3)

APPLICATION GUIDE FOR PHASE-TO-PHASE INSULATION

F-1. VOLTAGE STRESSES IN SERVICE

F-1.0 The dielectric stresses on phase-to-phase insulation may be classified as follows:

a) Power-frequency voltage under normal operating conditions,
b) Temporary overvoltages,
c) Switching overvoltages, and
d) Lightning overvoltages.

F-1.1 Power-Frequency Voltage — Under normal operating conditions the power-frequency voltage between phases will not be greater than the highest voltage for equipment U_m. Therefore, U_m has been taken as a reference value for insulation co-ordination purposes.

---

*Insulation co-ordination: Part 2 Phase-to-phase insulation co-ordination, principles and rules.

Gr 1

F-1.2 Temporary Overvoltages — The clauses of phase-to-phase temporary overvoltage are the same as those of the phase-to-earth temporary overvoltges described in the Standard, except for earth faults which, normally, do not create significant temporary phase-to-phase overvoltages (less than 1·2 U_m).

The insulation performance under temporary overvoltages, which are normally of short duration generally less than one second, is verified by the power-frequency test at voltage levels indicated in Tables 1 and 2 of IS : 2165 (Part 2)-1983* for the ranges A and B or specified in certain cases by the relevant Apparatus Committees for range C.

F-1.3 Switching Overvoltages — External phase-to-phase insulation is determined by considering the actual stresses due to switching operations, faults and other causes, the behaviour of the insulation when subjected to these stresses and the accepted risk of failure.

F-1.3.1 *Overvoltages Stresses* — The overvoltage between two phases results from two overvoltages to earth, generally having opposite polarity. Experience shows that various combinations of these overvoltages can occur. Nevertheless, the phase-to-phase overvoltage on a three-phase system may be characterized by two situations:

Situation 1 : When the peak of the highest phase-to-phase overvoltage is reached on any phase of the three-phase system;

Situation 2 : When the peak of the highest overvoltage between phases is attained for any two phases.

From these two situations the two phase-to-phase components of the phase-to-phase overvoltage are determined. Whilst, by definition the phase-to-phase earth voltage is always greater in situation 1, it should be noted that the maximum value of the phase-to-phase overvoltage obtained in situation 2 is greater than that obtained in situation 1.

The ratio usually observed between the statistical phase-to-phase overvoltage (situation 2) and the statistical phase-to-phase overvoltage (highest component of situation 1) lies in the range of 1·5 and 1·8, the values being greater for the higher system voltages. These ratios are the basis for the selection of rated switching-impulse withstand voltage phase-to-phase with respect to the phase-to-earth values.

F-1.3.2 *Insulation Behaviour* — The behaviour of any insulation depends on the geometric field distribution and on the type of the dielectric material.

In the case of external clearances and for a given total phase-to-phase test voltage, the division into components using the highest possible positive component on the one electrode (and the negative component on the other) is the most severe condition.

---

*Insulation co-ordination: Part 2 Phase-to-phase insulation co-ordinations principles and rules.

However, a different division may be used when testing the insulation provided that the same test severity is achieved by increasing the total phase-to-phase test voltage. The effect of the third phase voltage is generally small and can be neglected in most cases.

For the internal insulation, for example, transformers, it seems that the division of the components is of no importance. For other types of insulation, for example, SF_6 insulated, three phase enclosed installations the influence of the components has not yet been sufficiently investigated.

F-1.3.3 *Risk of Failure* — Evaluations of the risk of failure between phases have to take into account the division of the phase-to-phase overvoltage into two phase-to-earth components, the statistical distribution of the maximum phase-to-phase overvoltages and the flashover probability of the insulation. Such calculations have been made based on available system data and typical insulation withstand characteristics. The main results show that:

a) the two situations mentioned in **F.1.3.1** result in approximately the same risk of failure; and

b) the risk of failure between phases is smaller than (or equal to) that between phase and earth if the phase-to-earth insulation is tested according to IS : 2165 (Part 1)-1977* and if the phase-to-phase tested in the same way considering the test procedure given in **F-1.3.4.**

F-1.3.4 *Test Procedure* — To achieve the desired correlation between risks of failure between phases and phase-to-earth the withstand voltage of the insulation has to be equal to or greater than the rated switching-impulse withstand voltages given in Table 3 of IS : 2165 (Part 2)-1983†. To fulfil this requirement one of the test procedures given in IS : 2165 (Part 1)-1977* has to be applied. The permitted number of disruptive discharges includes all discharges between phases and to earth. Among the different division of components which are possible, according to **F-1.3.2** the one which is preferred is that giving the same amplitude to both components ($U_{neg}/U_{pos} = 1$). The main reasons are:

a) during the phase-to-phase test the phase-to-phase component shall not be higher than the rated switching-impulse withstand voltage to earth. Taking into account the values given in Table 3 of IS : 2165 (Part 2)-1983† this implies a ratio U_{neg}/U_{pos} already higher than 0·73. A further increase of this ratio is necessary to avoid an excessive number of flashovers to earth because of the influence of the negative component applied to the second phase;

---

*Insulation co-ordination: Part 1 Phase-to-earth insulation co-ordination, principles and rules.

†Part 2 Phase-to-phase insulation co-ordination, principles and rules.

b) for asymmetric test arrangements only two test series, applying the positive component successively to the two phases are required. If the ratio is different from 1, four test series are necessary to cover all cases by permuting the polarities and the values; and

c) the influence of surrounding objects during the test is kept to a minimum.

The selection of the ratio $U_{neg}/U_{pos} = 1$ results in a maximum acceptable risk of failure between phases which is lower than the maximum acceptable risk of failure to earth.

F-1.4 Lightning Overvoltages — When a direct lightning stroke occurs to a phase conductor or a backflashover takes place the lightning stress between phases does not normally exceed the lightning stress to earth.

F-2. CLEARANCE IN AIR BETWEEN PHASES TO ASSURE A SPECIFIED IMPULSE WITHSTAND VOLTAGE IN INSTALLATIONS

F-2.1 In complete installations (for example substation) which cannot be impulse-tested as a whole, it is necessary to ensure that the impulse strength is adequate.

The statistical switching- and lightning-impulse withstand voltages for phase-to-phase insulation in air should be equal to, or greater than, the rated switching- and lightning-impulse withstand voltages as specified in this standard. Following this principle minimum clearances have been determined for different electrode configurations.

Tables 7 and 8 are suitable for general application, as they provide a specified minimum clearance in relation to the insulation level. These clearances may be lower if it has been proved by tests on actual or similar configurations that the required rated impulse withstand voltages are fulfilled, taking into account all relevant environmental conditions which can create irregularities on the surface of the phase electrode, for example, rain, pollution.

As regards range *C*, lower clearances may also be used if it has been confirmed by operating experience that the switching overvoltages are lower than the rated values indicated in Table 3 of IS : 2165 (Part 2)-1983* for a given voltage U_m.

No distance is indicated for an equipment which has a phase-to-phase impulse test *included in the specification, since mandatory clearances* might hamper the design of the equipment, increase its cost and impede progress.

In Table 7 ($U_m < 300$kV), first column, the rated lightning-impulse withstand voltages are listed. The second column lists air clear-

---

***Insulation co-ordination: Part 2 Phase-to-phase insulation co-ordination, principles and rules.**

ances for unfavourable configurations of energized parts with a relatively small curvature radius. These clearances have been derived by the testing procedure described in 8 of IS : 2165 (Part 2)-1983*.

In the first column of Table 8 ($U_m \geqslant 300$ kV) rated switching-impulse withstand voltages phase-to-phase are listed. The second column lists clearances for a conductor-conductor (parallel) configuration having a symmetrical gap geometry. The same clearances may also be used for other configurations with symmetrical gap geometry such as crossed conductors of rod-rod gaps.

The third column refers to a configuration such as rod-conductor having an asymmetrical gap geometry.

For ring-ring gaps or configurations with large smooth electrodes having a higher degree of field homogeneity, lower clearances than those given in the second column may be used, provided that the influence of the environmental conditions (*see* above) is taken into account.

The clearances for the phase-to-phase insulation (*see* Tables 7 and 8) can be applied together with the clearances for the phase-to-earth insulation.

TABLE 7 CORRELATIONS BETWEEN INSULATION LEVELS AND MINIMUM PHASE-TO-PHASE AIR CLEARANCES FOR $U_m < 300$ kV

(*Clause* F-2.1)

RATED LIGHTNING-IMPULSE WITHSTAND VOLTAGE, PHASE-TO-PHASE (PEAK) (1) kV	MINIMUM PHASE-TO-PHASE AIR CLEARANCES (2) mm
20	60
40	60
60	90
75	120
95	160
125	220
145	270
170	320
250	480
325	630
450	900
550	1 100
650	1 300
750	1 500
850	1 700
950	1 900
1 050	2 100

---

*Insulation co-ordination: Part 2 Phase-to-phase insulation co-ordination principles and rules.

The values of air clearances given in Table 7 and 8 are dictated by dielectric considerations. Other factors such as construction tolerances, the effect of short circuits, wind, safety of personnel, maintenance, corona effects etc. are not included.

The indicated values are valid for altitudes not exceeding 1 000 m. The effects of higher altitudes are under consideration.

TABLE 8 CORRELATION BETWEEN INSULATION LEVELS AND MINIMUM PHASE-TO-PHASE AIR CLEARANCES FOR $U_{\mathrm{m}} > 300$ kV

(*Clause* F-2.1)

Rated Switching-Impulse Withstand Voltage Phase-to-Phase (Peak)	Minimum Phase-to-Phase Air Clearance for Configurations	
	Conductor-Conductor Parallel	Rod-Conductor
(1) kV	(2) m	(3) m
1 175	2·4	2·8
1 300	2·7	3·2
1 425	3·1	3·6
1 550	3·5	4·1
1 675	3·9	4·6
1 800	4·3	5·2
1 950	4·9	5·9
2 100	5·6	6·8
2 250	6·3	7·7
2 400	7·1	8·8
2 550	7·9	10·0

(ETDC 19)

Printed at Simco Printing Press, Delhi, India